DOCUMENT RESUME

ED 044 297 SE 010 095

TITLE	Control Techniques for Particulate Air Pollutants.
INSTITUTION	Public Health Service (DHEW), Washington, D.C. National Air Pollution Control Administration.
REPORT NO	Pub-AP-51
PUB DATE	Jan 69
NOTE	241p.
AVAILABLE FROM	Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Cat. No. FS 2.93/3:51, $1.75)
EDRS PRICE	EDRS Price MF-$1.00 HC Not Available from EDRS.
DESCRIPTORS	*Air Pollution Control, *Environment, Environmental Influences, *Pollution, *Resource Materials

ABSTRACT

Included is a comprehensive review of the approaches commonly recommended for controlling the sources of particulate air pollution. Not all possible combinations of control techniques that might bring about more stringent control of each individual source are reviewed. The many agricultural, commercial, domestic, industrial, and municipal processes and activities that generate particulate air pollutants are described individually and the various techniques that can be applied to control emissions of particulate matter from these sources are reviewed and compared. A technical consideration of the most important types of gas cleaning devices forms a major segment of the document, while sections on source evaluation, equipment costs and cost-effectiveness analysis, and current research and development are also included. The bibliography contains important reference articles, arranged according to applicable processes. (Author/PR)

ED044297

CONTROL TECHNIQUES FOR PARTICULATE AIR POLLUTANTS

U.S. DEPARTMENT OF HEALTH, EDUCATION & WELFARE
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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Consumer Protection and Environmental Health Service

ED0 44297

CONTROL TECHNIQUES
FOR
PARTICULATE AIR POLLUTANTS

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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National Air Pollution Control Administration
Washington, D.C.
January 1969

National Air Pollution Control Administration Publication No. AP–51

Preface

Throughout the development of Federal air pollution legislation, the Congress has consistently found that the States and local governments have the primary responsibility for preventing and controlling air pollution at its source. Further, the Congress has consistently declared that it is the responsibility of the Federal government to provide techical and financial assistance to State and local governments so that they can undertake these responsibilities.

These principles were reiterated in the Air Quality Act of 1967. A key element of that Act directs the Secretary of Health, Education, and Welfare to collect and make available information on all aspects of air pollution and its control. Under the Act the issuance of control techniques information is a vital step in a program designed to assist the States in taking responsible technological, social, and political action to protect the public from the adverse effects of air pollution.

Briefly, the Act calls for the Secretary of Health, Education, and Welfare to define the broad atmospheric areas of the Nation in which climate, meteorology, and topography, all of which influence the capacity of air to dilute and disperse pollution, are generally homogeneous.

Further, the Act requires the Secretary to define those geographical regions in the country where air pollution is a problem—whether interstate or intrastate. These air quality control regions are designated on the basis of meteorological, social, and political factors which suggest that a group of communities should be treated as a unit for setting limitations on concentrations of atmospheric pollutants. Concurrently, the Secretary is required to issue air quality criteria for those pollutants he believes may be harmful to health or welfare, and to publish related information on the techniques which can be employed to control the sources of those pollutants.

Once these steps have been taken for any region, and for any pollutant or combination of pollutants, then the State or States responsible for the designated region are on notice to develop ambient air quality standards applicable to the region for the pollutants involved, and to develop plans of action for meeting the standards.

The Department of Health, Education and Welfare will review, evaluate, and approve these standards and plans and, once they are approved, the States will be expected to take action to control pollution sources in the manner outlined in their plans.

At the direction of the Secretary, the National Air Pollution Control Administration has established appropriate programs to carry out the several Federal responsibilities specified in the legislation.

Control Techniques for Particulate Air Pollutants is the first of a series of documents to be produced under the program established to carry out the responsibility for developing and distributing control technology information. The document is the culmination of intensive and dedicated effort on the part of many persons.

In accordance with the Air Quality Act, a National Air Pollution Control Techniques Advisory Committee was established, having a membership broadly representative of industry, universities, and all levels of government. The committee, whose members are listed following this discussion, provided invaluable advice in identifying the best possible methods for controlling the sources of particulate air pollution, assisted in determining the costs involved, and gave major assistance in drafting this document.

As further required by the Air Quality

Act, appropriate Federal departments and agencies, also listed on the following pages, were consulted prior to issuance of this document. A Federal consultation committee, comprising members designated by the heads of 17 departments and agencies, reviewed the document, and met with staff personnel of the National Air Pollution Control Administration to discuss its contents.

During 1967, at the initiation of the Secretary of Health, Education, and Welfare, several government-industry task groups were formed to explore mutual problems relating to air pollution control. One of these, a task group on control technology research and development, looked into ways that industry representatives could participate in the review of the control techniques reports. Accordingly, several industrial representatives, listed on the following pages, reviewed this document and provided helpful comments and suggestions. In addition, certain consultants to the National Air Pollution Control Administration also reviewed and assisted in preparing portions of this document. (These also are listed on the following pages.)

The Administration is pleased to acknowledge the efforts of each of the persons specifically named, as well as those of the many not so listed who contributed to the publication of this volume. In the last analysis, however, the National Air Pollution Control Administration is responsible for its content.

The control of air pollutant emissions is a complex problem because of the variety of sources and source characteristics. Technical factors frequently make necessary the use of different control procedures for different types of sources. Many techniques are still in the developmental stage, and prudent control strategy may call for the use of interim methods until these techniques are perfected. Thus, we can expect that we will continue to improve, refine, and periodically revise the control technique information so that it will continue to reflect the most up-to-date knowledge available.

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SUMMARY

PARTICULATE SOURCES

Particulate material found in ambient air originates from both stationary and mobile sources. Of the 11.5 million tons of particulate pollution produced by industrial, commercial, and domestic sources in 1966, 6 million tons were emitted from industrial sources, including industrial fuel burning; 5 million tons from power generation, incineration, and space heating; and 0.5 million ton from mobile sources.

The following techniques are in use for controlling the source or reducing the effects of particulate pollution:

1. Gas cleaning
2. Source relocation
3. Fuel substitution
4. Process changes
5. Good operating practice
6. Source shutdown
7. Dispersion

Internal Combustion Engines

Although particulate emissions from internal combustion engines are estimated to contribute only 4 percent of the total particulate emissions on a nationwide basis, they do contribute as much as 38 percent in certain urban areas. The relative percentages of particulate emissions for this and other source categories differ from one area to another depending on automobile density, degree of stationary source control, and types of sources present in the area.

For each 1000 gallons of fuel consumed, diesel-fueled engines produce about 110 pounds of particulate matter. Gasoline-fueled engines produce about 12 pounds per 1000 gallons of fuel consumed.

Gasoline engine-produced particulate matter emanates from the crankcase and exhaust gases. It consists of carbon, metallic ash, aerosol hydrocarbons, and metallic particles.

The particulate matter emitted from a diesel engine comprises carbon and hydrocarbon aerosols. Control of diesel engine emissions effects reduction in smoke.

Stationary Combustion Sources

In the United States more than 29 million stationary combustion sources are currently in operation. About 2 percent are fired with coal, 61 percent are fired with gas, and 37 percent are fired with fuel oil. The relative usage of fuels on a Btu basis shows coal to be 32 percent, natural gas 49 percent, and fuel oil 19 percent.

Types of gas cleaning devices currently being used for stationary combustion sources are listed in Table 1. Newer control systems are now being installed which will be used to control both particulate matter and sulfur oxides.

Industrial Sources

Industrial processes, including industrial fuel burning, discharged an estimated 6.0 million tons of particulate materials in 1966. This amounts to more than 50 percent of the total particulate pollution on a nationwide basis. Major pollutants are dusts, fumes, oils, smoke, and mists.

Table 2 presents a summary of important industries, their pollutant sources, particu-

Table 1.—TYPICAL PRESSURE DROPS AND EFFICIENCY RANGES FOR GAS CLEANING DEVICES USED FOR STATIONARY COMBUSTION SOURCES

Unit	Pressure drop, in. H_2O	Efficiency, percent
Settling chambers	0.5	20–60
Large-diameter cyclones	0.5–4.0	30–65
Small-diameter cyclones	2–8	70–90
Electrostatic precipitator	0.1–0.5	75–99.5

Table 2.—INDUSTRIAL PROCESS AND CONTROL SUMMARY

Industry or process	Source of emissions	Particulate matter	Method of control
Iron and steel mills	Blast furnaces, steel making furnaces, sintering machines.	Iron oxide, dust, smoke	Cyclones, baghouses, electrostatic precipitators, wet collectors.
Gray iron foundries	Cupolas, shake out systems, core making.	Iron oxide, dust, smoke, oil, grease, metal fumes.	Scrubbers, dry centrifugal collectors.
Metallurgical (non-ferrous)	Smelters and furnaces	Smoke, metal fumes, oil, grease.	Electrostatic precipitators, fabric filters.
Petroleum refineries	Catalyst regenerators, sludge incinerators.	Catalyst dust, ash from sludge.	High-efficiency cyclones, electrostatic precipitators, scrubbing towers, baghouses.
Portland cement	Kilns, dryers, material handling systems.	Alkali and process dusts	Fabric filters, electrostatic precipitator, mechanical collectors.
Kraft paper mills	Chemical recovery furnaces, smelt tanks, lime kilns.	Chemical dusts	Electrostatic precipitators, venturi scrubbers.
Acid manufacture-phosphoric, sulfuric.	Thermal processes, phosphate rock acidulating, grinding and handling systems.	Acid mist, dust	Electrostatic precipitators, mesh mist eliminators.
Coke manufacturing	Charging and discharging oven cells, quenching, materials handling.	Coal and coke dusts, coal tars.	Meticulous design, operation, and maintenance.
Glass and glass fiber	Raw materials handling, glass furnaces, fiberglass forming and curing.	Sulfuric acid mist, raw materials dusts, alkaline oxides, resin aerosols.	Glass fabric filters, afterburners.
Coffee processing	Roasters, spray dryers, waste heat boilers, coolers, conveying equipment.	Chaff, oil aerosols, ash from chaff burning, dehydrated coffee dusts.	Cyclones, afterburners, fabric filters.

late pollutants, and air cleaning techniques (equipment) presently in use.

Construction and Demolition

The principal demolition, construction, and related operations that generate particulate air pollution are:

1. Demolition of masonry
2. Open burning
3. Movement of vehicles on unpaved roads
4. Grading of earth
5. Paving of roads and parking lots
6. Handling and batching of paving materials
7. Sandblasting of buildings
8. Spray painting

Control of the above operations is accomplished by various means which include hooding and venting to air pollution control equipment, wetting down working surfaces with water or oil, and using sanitary landfill.

Solid Waste Disposal

Although solid waste disposal by incineration accounts for less than 10 percent of the total particulate pollution (1 million tons in 1966), it does, however, inspire many complaints about air pollution. Of the 190 million tons of solid wastes collected in 1967, 86 percent went into land disposal sites, 8 percent was burned in municipal incinerators, and 6 percent was disposed of in sanitary landfills. Since open burning is practiced at three-fourths of the land disposal sites, particulate emissions from these sites contribute significantly to air pollution arising from the disposal of solid waste.

Over 70 percent of existing municipal incinerators were installed before 1960, and lack adequate provisions for eliminating particulate emissions.

An obvious means of reducing the air pollution resulting from solid waste disposals is to use such non-incineration methods for disposal as follows:

1. Sanitary landfill
2. Composting
3. Shredding and grinding
4. Dispersion (hauling to another locale)

These methods contribute little to air pollution problems.

It is estimated that measures to upgrade existing land disposal sites, and thus do away with open burning, will cost as much as $230 million per year for 5 years.

Where incineration is used for solid waste disposal, the principal particulate pollutant emitted is fly ash. Its removal from effluent gas streams is accomplished by low pressure drop (0.5 inch H_2O) scrubbers, or settling chambers.

The estimated cost of upgrading or replacing existing inadequate municipal incinerators is $225 million, of which $75 million would be for air pollution control equipment.

GAS CLEANING DEVICES

It has been estimated that total expenditures in 1966 on industrial air pollution control equipment in the United States were about $235 million. Value of shipments of the industrial gas cleaning equipment industry in 1967 was double the 1966 figure, and the backlog of orders recently nearly equalled a year's productive output. Undoubtedly legislative pressure and local pollution control regulations have supplied the impetus for such rapid growth in this industry.

The selection of gas cleaning equipment is far from an exact science and must be based on characteristics of particle and carrier gas, and process, operation, construction, and economic factors. Information on particle size gradation in the inlet gas stream is important in the proper selection of gas cleaning equipment. Particles larger than 50 microns may be removed satisfactorily in inertial and cyclone separators and simple, low-energy wet scrubbers. Particles smaller than 1 micron can be arrested effectively by electrostatic precipitators, high-energy scrubbers, and fabric filters.

Table 3 lists advantages and disadvantages in applicability of each of the general types of air cleaners to given situations.

EMMISSION FACTORS

Emission factors may be used to estimate emissions from sources for which accurate stack test results are unavailable. Process emission factors for some selected source types are presented in Table 4.

ECONOMICS

Air pollution control is viewed not only from the standpoint of available technology but also with respect to the economic feasibility of control methods and/or equipment.

Among the cost elements relevant to an air pollution control problem are:

1. Capital costs of control equipment.
2. Depreciation of all control equipment.
3. Overhead costs including taxes, insurance, and interest for control equipment.
4. Operation and maintenance costs.
5. Collected waste material disposal costs.
6. Other capital expenditures for research and development, land, and engineering studies to determine and design optimum control system.

Many of these elements differ from one installation to another. Table 5 lists major collector types and their approximate installed costs for operational air flow rates. The installed costs (purchase cost, transportation, and preparation for on line operation) are average costs for typical control equipment.

Table 6 presents generalized operating and maintenance cost equations for various types of control equipment.

BIBLIOGRAPHY

A list of references follows each section of this document. Other references relating to control technology for generic sources of particulate air pollutants are cited in the bibliography, which comprises the final section. Although all of the articles cited in the bibliography do not necessarily reflect the most modern control practices, they do provide useful background material on the control technology for particulate air pollutants.

Table 3.—ADVANTAGES AND DISADVANTAGES OF COLLECTION DEVICES

Collector	Advantages	Disadvantages
Gravitational	Low pressure loss, simplicity of design and maintainance.	Much space required. Low collection efficiency.
Cyclone	Simplicity of design and maintainance	Much head room required.
	Little floor space required	Low collection efficiency of small particles.
	Dry continuous disposal of collected dusts	Sensitive to variable dust loadings and flow rates.
	Low to moderate pressure loss.	
	Handles large particles.	
	Handles high dust loadings.	
	Temperature independent.	
Wet collectors	Simultaneous gas absorption and particle removal.	Corrosion, erosion problems. Added cost of wastewater treatment and reclamation.
	Ability to cool and clean high-temperature, moisture-laden gases.	Low efficiency on submicron particles.
	Corrosive gases and mists can be recovered and neutralized.	Contamination of effluent stream by liquid entrainment.
	Reduced dust explosion risk	Freezing problems in cold weather.
	Efficiency can be varied	Reduction in buoyancy and plume rise. Water vapor contributes to visible plume under some atmospheric conditions.
Electrostatic precipitator.	99+ percent efficiency obtainable	Relatively high initial cost.
	Very small particles can be collected	Precipitators are sensitive to variable dust loadings or flow rates.
	Particles may be collected wet or dry	Resistivity causes some material to be economically uncollectable.
	Pressure drops and power requirements are small compared to other high-efficiency collectors.	Precautions are required to safeguard personnel from high voltage.
	Maintenance is nominal unless corrosive or adhesive materials are handled.	Collection efficiencies can deteriorate gradually and imperceptibly.
	Few moving parts	
	Can be operated at high temperatures (550° to 850° F.).	
Fabric filtration	Dry collection possible	Sensitivity to filtering velocity.
	Decrease of performance is noticeable	High-temperature gases must be cooled to 200° to 550° F.
	Collection of small particles possible	Affected by relative humidity (condensation).
	High efficiencies possible	Susceptibility of fabric to chemical attack.
Afterburner, direct flame.	High removal efficiency of submicron odor-causing particulate matter.	High operational cost. Fire hazard.
	Simultaneous disposal of combustible gaseous and particulate matter.	Removes only combustibles.
	Direct disposal of non-toxic gases and wastes to the atmosphere after combustion.	
	Possible heat recovery	
	Relatively small space requirement	
	Simple construction	
	Low maintenance	
Afterburner, catalytic.	Same as direct flame afterburner	High initial cost.
	Compared to direct flame: reduced fuel requirements, reduced temperature, insulation requirements, and fire hazard.	Catalysts subject to poisoning. Catalysts require reactivation.

Table 4.—EXAMPLES OF PARTICULATE EMISSION FACTORS

Source	Specific process	Particulate emission rate, uncontrolled
Aircraft	Four engine fan jet	7.4 lb/flight.
Solid waste disposal	Open burning dump	16 lb/ton of refuse.
Phosphoric acid manufacturing.	Thermal process	0.2–10.8 lb/ton of phosphorus burned.
Sulfuric acid manufacturing.	Contact process	0.3–7.5 lb/ton of acid produced.
Food and agricultural	Coffee roasting, direct fired	7.6 lb/ton of green beans.
	Cotton ginning and incineration of trash	11.7 lb/bale of cotton.
Feed and grain mills	General operation	6 lb/ton of product.
Primary metal industry	Iron and steel manufacturing furnace, open hearth (oxygen lance).	22 lb/ton of steel.
Secondary metal industry	Aluminum smelting, chlorination-lancing	1000 lb/ton of chlorine.
	Brass and bronze smelting reverberatory furnace.	26.3 lb/ton of metal charged.
	Gray iron foundry cupola	17.4 lb/ton of metal charged.

Table 5.—INSTALLED COSTS OF CONTROL EQUIPMENT

Collector type	Approximate installed cost, in thousands of dollars						
	Gas flow rates (1000 actual cubic feet per minute)						
	2	5	10	15	100	300	500
Gravity	0.5	1.2	2.6	15	28	------	------
Mechanical	------	------	4	13	23	80	------
Wet	------	7.5	10	30	55	150	------
High-voltage electrostatic precipitator	------	------	------	85	120	265	415
Low-voltage electrostatic precipitator	------	13	24	105	200	------	------
Fabric filter:							
High temperature (550° F.)	------	------	30	88	155	430	720
Medium temperature (250° F.)	------	------	15	45	82	225	375
Afterburner, direct flame catalytic	8.2	12	18	------	------	------	------
	16	20	29	------	------	------	------

Table 6.—GENERALIZED ANNUAL OPERATING AND MAINTENANCE COST EQUATIONS FOR CONTROL EQUIPMENT

Collector	Generalized equation
Mechanical centrifugal collector	$G=S\left[\frac{0.7457\ PHK}{6356\ E}+M\right]$
Wet collector	$G=S\left[0.7457\ HK\left(Z+\frac{Qh}{1980}\right)+WHL+M\right]$
Electrostatic precipitator	$G=S\,[(JHK+M)]$
Fabric filter	$G=S\left[\frac{0.7457\ PHK}{6356\ E}+M\right]$
Afterburner	$G=S\left[\frac{0.7457\ PHK}{6356\ E}+FH+M\right]$

Where:

G = annual costs, dollars, for operating and maintenance
S = design capacity of the unit, actual cubic feet per minute (acfm)
P = pressure drop, inches of water
H = hours of operation annually
K = cost of electricity; dollars per kilowatt-hour
E = fan efficiency expressed as decimal
M = maintenance cost per acfm, dollars per cfm
F = fuel cost, dollars per acfm per hour
W = make-up liquid rate in gallons per hour per acfm
L = cost of liquid in dollars per gallon
Z = total power input required for a specified scrubbing efficiency, horsepower per acfm
J = kilowatts of electricity per acfm
h = elevation for pumping of liquor in circulation system for collector, feet
Q = water circulation, gallons per acfm

1. INTRODUCTION

Pursuant to authority delegated to the Commissioner of the National Air Pollution Control Administration, *Control Techniques for Particulate Air Pollutants* is issued in accordance with Section 107c of the Clean Air Act (42 U.S.C. 1857c–2b1).

Particulate matter in the atmosphere is known to have many adverse effects upon health and welfare, and reduction of emissions of this pollutant is of prime importance to any effective air pollution abatement program. Particulate pollutants originate from a variety of sources, and the emissions vary widely in physical and chemical characteristics. Similarly, the available control techniques vary in type, application, effectiveness, and cost.

The control techniques described herein represent a broad spectrum of information from many engineering and other technical fields. The devices, methods, and principles have been developed and used over many years, and much experience has been gained in their application. They are recommended as the techniques generally applicable to the broad range of particulate emission control problems.

The proper choice of a method, or combination of methods, to be applied to any specific source depends on many factors other than the characteristics of the source itself. While a certain percentage of control, for example, may be acceptable for a single source, a much higher degree may be required for the same source when its emissions blend with those of others. This document provides a comprehensive review of the approaches commonly recommended for controlling the sources of particulate air pollution. It does not review all possible combinations of control techniques that might bring about more stringent control of each individual source.

The many agricultural, commercial, domestic, industrial, and municipal processes and activities that generate particulate air pollutants are described individually in this document. The various techniques that can be applied to control emissions of particulate matter from these sources are reviewed and compared. A technical consideration of the most important types of gas cleaning devices forms a major segment, while sections on source evaluation, equipment costs and cost-effectiveness analysis, and current research and development also are included. The bibliography contains important reference articles, arranged according to applicable processes.

While some data are presented on quantities of particulate matter emitted to the atmosphere, the effects of particulate matter on health and welfare are considered in a companion document, *Air Quality Criteria for Particulate Matter.*

2. BACKGROUND INFORMATION

2.1 DEFINITIONS

This section contains general definitions of the terms used throughout this document.

Pollutant or Contaminant—any solid, liquid, or gaseous matter in the outdoor atmosphere which is not normally present in natural air.

Particulate Matter—as related to control technology, any material, except uncombined water, that exists as a solid or liquid in the atmosphere or in a gas stream at standard conditions.

It is important that standard conditions for the measurement of particulate matter be included with its definition. Some compounds are not solids or liquids at stack conditions but condense in the ambient atmosphere. Unless standard conditions for measurement of particulate matter are defined, these materials would not be considered particulate and subject to control.

Aerosol—a dispersion in gaseous media of solid or liquid particles of microscopic size, such as smoke, fog, or mist.

Dust—solid particles predominantly larger than colloidal size and capable of temporary suspension in air and other gases. Derivation from larger masses through the application of physical force is usually implied.

Fly Ash—finely divided particles of ash entrained in flue gasses arising from the combustion of fuel. The particles of ash may contain unburned fuel and minerals.

Fog—visible aerosols in which the dispersed phase is liquid. In meteorology, fog is a dispersion of water or ice.

Fume—particles formed by condensation, sublimation, or chemical reaction, of which the predominant part, by weight, consist of particles smaller than 1 micron. Tobacco smoke and condensed metal oxides are examples of fume.

Mist—low-concentration dispersion of relatively small liquid droplets. In meteorology, the term mist applies to a light dispersion of water droplets of sufficient size to fall from the air.

Particle—small, discrete mass of solid or liquid matter.

Smoke—small gasborne particles resulting from incomplete combustion. Such particles consist predominantly of carbon and other combustible material, and are present in sufficient quantity to be observable independently of other solids.

Soot—an agglomeration of carbon particles impregnated with "tar," formed in the incomplete combustion of carbonaceous material.

Sprays—liquid droplets formed by mechanical action.

2.2 MAJOR SOURCES OF PARTICULATE MATTER

An estimated 11.5 million tons of particulate matter was emitted from industrial, commercial, and domestic sources in the United States during 1966.[1] Particulate matter, emitted from sources other than these, includes ocean salt, volcanic ash, wind erosion

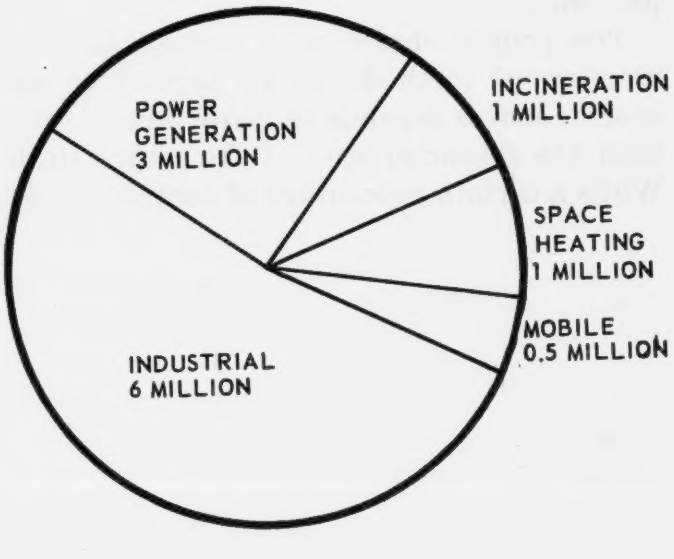

FIGURE 2–1. Sources of particulate matter and quantities produced in tons per year.

and roadway dust, forest fire smoke, and plant seed and pollen. Figure 2–1, which is based on Reference 1 and gasoline and fuel consumption figures, shows that industrial sources of particulate matter, including industrial fuel burning, emit 6 million tons of particulate matter annually. About 5 million tons result annually from power generation, incineration,* and space heating. Mobile (transportation) sources emit the remaining 0.5 million tons.

2.2.1 Combustion Sources

Combustion of coal and oil results in an annual emission of 4.5 million tons of particulate matter that is principally fly ash from coal combustion. Emission sources are discussed in Section 3.3 of this report.

Refuse burning, both in incinerators and in dumps, produces approximately 1 million tons of particulate matter annually. Much of this particulate matter is dust, fume, smoke, fly ash, and large pieces of partially burned refuse. Although refuse burning creates less than 15 percent of the total particulate matter emitted in the United States, such emissions are usually concentrated in heavily populated areas and have a more significant impact on the population than these statistics may suggest.

2.2.2 Industrial Sources

Particulate emissions from industrial processes consist of dust, fume, smoke, and mist arising largely from combustion and loss of process materials or products to the atmosphere. Such emissions totaled 6 million tons in 1966. Major industrial sources are listed and discussed in Section 3.4 of this report.

In some industrial processes, efficient collection of particulate matter increases overall plant operating efficiency by recovering a portion of the product that would otherwise be lost to the atmosphere. Dust collectors used in cement plants, grain handling operations, and carbon black plants can recover valuable products.

2.2.3 Mobile Sources

Emissions from mobile sources, which total approximately 0.5 million tons of particulate matter per year, are largely caused by the burning of fuels in motor vehicles. Automobile exhaust is the largest source of particulate matter in this category. It is characterized by an extremely large number of fine particles consisting of organic and inorganic materials, including lead. Particulate emissions from diesel engines are more concentrated and may cause a visible plume. Aircraft, especially jet-powered planes, also produce visible particulate emissions. The emission rate is greatest during takeoff and landing operations when the engines operate under conditions of a high ratio of fuel to air.

REFERENCE FOR SECTION 2

1. "The Sources of Air Pollution and Their Control." U.S. Dept. of Health, Education, and Welfare, Div. of Air Pollution, Washington, D.C., PHS–Pub–1548, 1966.

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*Does not include agricultural burning and forest fires.

3. PARTICULATE SOURCES AND CONTROLS

3.1 INTRODUCTION

The earliest approaches to air pollution control, used in England over 200 years ago, were the restriction of smoke releases and relocation of sources to "offensive trades zones." The latter was used particularly when the odor of the source was offensive. Relocation is still used, or at least considered, by operators of some pollution sources as an alternate to emissions control. In most instances, however, relocating a pollution source to a remote area may only postpone the adoption of emissions control.

Many sources such as transportation, space heating, and solid wastes disposal are inherent in population centers. All generate particulate air pollution in urban areas. Although remote power generation and long distance hauling of solid wastes are possible, automobiles, busses, incinerators, and home furnaces and manufacturing and commercial operations that require workers will, in all likelihood, continue to operate in our cities.

To appreciate the air pollution problem facing the United States, it is necessary to have some understanding of the sources of air pollution and the means of controlling them. The multitude of small sources closest to the average citizen—automobiles, home furnaces, on-site incinerators—are often the least effectively controlled. High-efficiency control equipment use is limited almost entirely to certain steam-electric generating stations and industrial operations, particularly the large installations. Most of the high-efficiency emissions controls are being developed for such sources as steel mills, steam-electric generating stations, petroleum refineries, and chemical plants. The most promising areas of improvement for small sources involve basic changes in source operation—cleaner fuels, automobile engine modifications, and improved means of solid wastes disposal.

3.2 INTERNAL COMBUSTION ENGINES

Although stationary sources are the major contributors of particulate matter, the motor vehicle contributes a significant amount of particulate matter to the atmosphere. The ranking of the motor vehicle emissions in an urban community is a function of the relative magnitude of the vehicular and industrial activities; the extent to which coal, residual fuels, and refuse are burned; and the extent and effectiveness of the air pollution control measures used. Each 1,000 gallons of fuel consumed by diesel engines produces about 110 pounds of particulate matter and gasoline engines produce about 12 pounds of particulate for every 1,000 gallons consumed.[1] Of the total annual emission of 11.5 million tons of particulate matter, motor vehicles contribute approximately 4 percent or about 500,000 tons.

Table 3–1 presents examples of contribution by motor vehicles to particulate emissions in different communities.

3.2.1 Gasoline-Fueled Vehicles

Particulate matter is emitted in the exhaust and crankcase blowby gases of gaso-

Table 3–1.—COMPARISON OF MOTOR VEHICLE PARTICULATE EMISSIONS WITH TOTAL PARTICULATE EMISSIONS FOR SELECTED AREAS [2-7]

Metropolitan area	Particulate matter, tons/yr Total	Motor vehicles	Percent of total from motor vehicles
Washington, D. C.	35,000	5,700	16
New York-Northern New Jersey	231,000	33,800	15
Kansas City	60,000	5,000	8
Jacksonville, Florida	14,000	600	4
St. Louis	147,000	4,700	3
Los Angeles County	43,000	16,400	38

line-fueled engines. Carbon, metallic ash, hydrocarbons in aerosol form, and metallic materials present in engine systems are emitted.

Metal-based particles result almost entirely from the use of lead antiknock compounds in the fuel; however, metallic lubricating oil additives and engine wear particles are also present. Carbon and some of the hydrocarbon aerosols result from incomplete combustion of fuel. The rest of the aerosols are emitted to the atmosphere from engines with vented crankcases or are produced by crankcase oil that leaks past the piston rings into the combustion chamber and is emitted unburned with the exhaust gases.

Particulate matter in automobile exhaust amounts to approximately 5 percent by weight of the amount of gaseous hydrocarbon emitted. It consists of lead compounds, carbon particles, motor oil, and nonvolatile reaction products formed from motor oil in the combustion zone. It is suspected that these reactions involve the formation of high-molecular-weight olefins, and carbonyl compounds.

Particles in blowby gases consist almost entirely of unchanged lubricating oil. As a very rough approximation, the amount of material emitted in blowby gases is one-third to one-half the amount emitted in the exhaust. The same approximate ratio applies to either particulate emission or gaseous hydrocarbon emission. Blowby emissions are influenced to a greater extent than exhaust emissions by mechanical condition of the engine.[8]

Partial control of vehicle particulate emissions has been in effect nationally since 1963. Beginning with the 1968 automobile models, the particulates in crankcase gases were completely controlled (Fig. 3–1). It is possible the exhaust emission control measures employed in the 1968 model passenger cars reduce the emissions of some particulates.

Technology for the control of lead in exhaust emissions is in the developmental stage. The National Air Pollution Control Administration is presently evaluating two prototype electrogasdynamic precipitators for gasoline and diesel motor vehicle exhausts.[9]

Lead emissions may also be controlled by restricting the concentration of lead antiknock compounds that are permitted in the fuel. The American Petroleum Institute indicates that the additional cost of unleaded fuel would be 1.8 to 4.7 cents per gallon. Petroleum processing equipment is available for producing unleaded gasoline, but an estimated 5 to 10 years is necessary for its installation at a capital investment of over $4 billion.[10, 11]

3.2.2 Diesel-Powered Vehicles

Particulate matter emitted by diesel engines consists primarily of carbon and hydrocarbon aerosols resulting from incomplete combustion of the fuel. Aerosols in the vent gases of the two-stroke-cycle diesel engine (from air box drains) and in the exhaust, as a result of crankcase oil going through the combustion process unburned, produce a small amount of additional particulate emissions.

Federal regulations scheduled for implementation in 1970 will limit smoke from new diesel engines. The regulations establish a maximum intensity of smoke emission (measured by reduction in light transmission) under conditions of severe engine loading at (1) full-throttle acceleration from a prolonged idle and (2) "lugdown" from maximum governed speed, also at full throttle. No new information or control devices are believed to be needed to reduce the smoke emissions from diesel engines to meet the established standards. As vehicle mileage increases, proper fuel system adjustment, maintenance at appropriate intervals, the use of the specified type of fuel, and good operating techniques can maintain low levels of visible emissions, particularly with respect to particulate carbon.

New engines, which will comply with the 1970 smoke standards, will be adjusted by the engine manufacturer to a conservative fuel rate and power output. Increases in fuel rate above the manufacturer's setting will increase engine power, but also will raise the level of black smoke. Even in a properly adjusted engine, injector deterioration (such as nozzle erosion) can effect a substantial increase in the emission of black smoke.

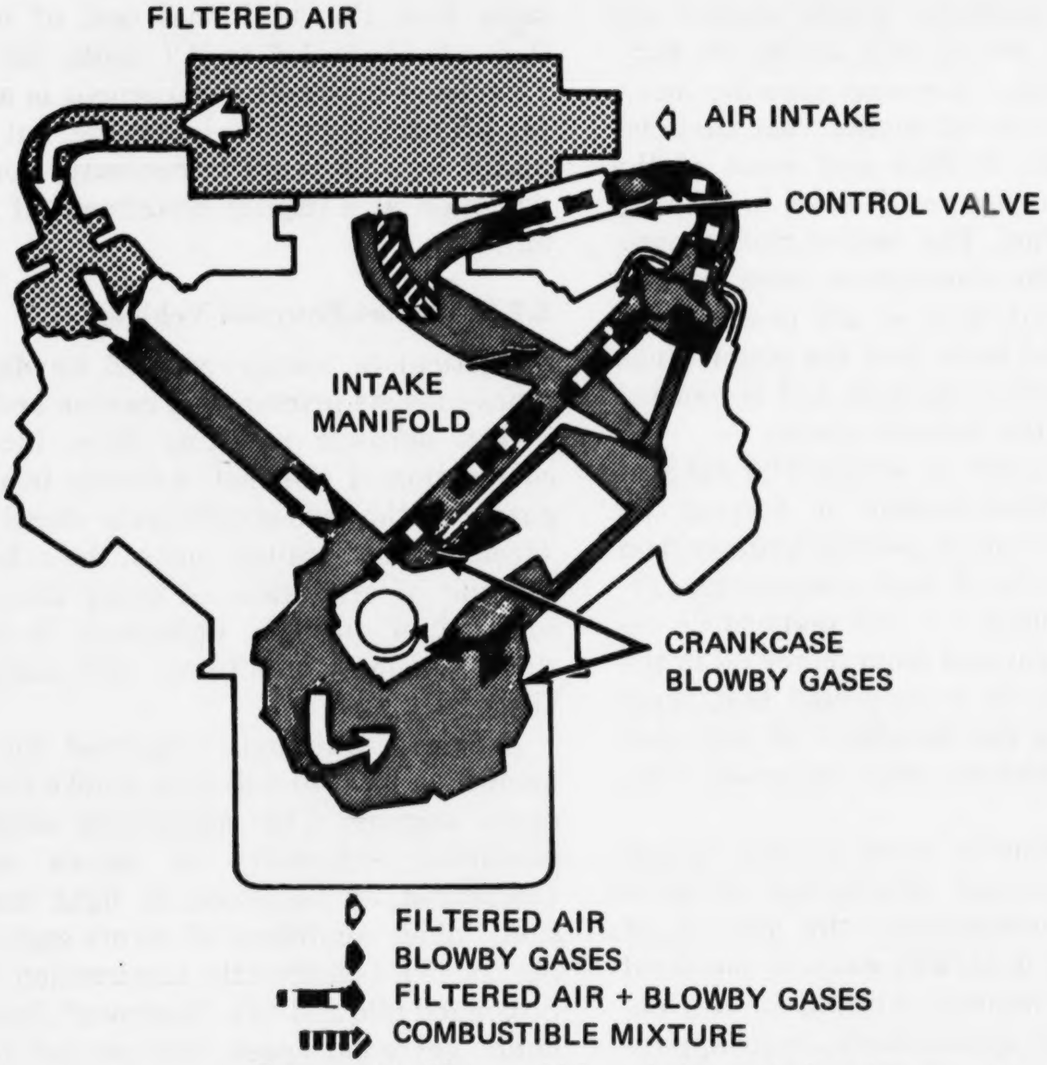

FIGURE 3–1. Motor vehicle emission control system.

Investigations have been conducted to evaluate methods of reducing diesel smoke. Methods consist primarily of exhaust gas dilution and the use of smoke-suppressing fuel additives. Neither of these methods can be recommended for general application at this time. The dilution technique at best, merely reduces the opacity of the smoke plume without reducing the quantity of particles emitted. Smoke suppressants have been reported to be effective in overfueled engines in good mechanical condition. One type of suppressant reported to show promise contains barium.[12] Use of the organic barium additive could, however, result in the emission of toxic, water-soluble, barium compounds. Further study of additives is needed before this technology can be broadly adopted.

3.3 CONTROL OF PARTICULATE EMISSIONS FROM STATIONARY COMBUSTION SOURCES

3.3.1 Introduction

3.3.1.1 General—Of the many techniques used to control particulate air pollution from stationary combustion sources, none has emerged as an all-inclusive answer to the control problem.

3.3.1.2 Sources—More than 29 million stationary combustion sources are currently in operation in the United States.[13] About 2 percent are fired with coal, 61 percent are fired with gas, and 37 percent are fired with liquid fuels. Table 3–2 shows the consumption of energy by type of consumer. Coal, gas, and oil are burned in a wide variety of equip-

Table 3–2.—ESTIMATED 1966 UNITED STATES ENERGY CONSUMPTION BY SELECTED CONSUMER (10^{12} Btu)[14]

Energy source	Consumer			
	Household and commercial	Industrial	Power generation	Total
Anthracite coal	143	41 [a]	56	240
Bituminous and lignite coal.	575	2,206 [a]	6,341	9,122
Natural gas	5,945	5,674 [a]	2,692	14,311
Petroleum [b]	2,247 [a]	2,512 [a]	905	5,664
Hydroelectric	0	0	2,060	2,060
Nuclear	0	0	58	58
Total	8,910	10,433	12,112	31,455

[a] Excludes non-combustion consumption.

[b] Excludes naphtha, kerosene, and liquified petroleum gases.

ment. The more common types of equipment are shown in Table 3–3.

3.3.1.3 Emissions—Particulate emissions from stationary combustion sources in the United States are estimated at 4.5 million tons (see Table 3–4). Local patterns of emissions will usually differ from the national pattern because of differences in fuel and equipment use patterns.

The rate of uncontrolled particulate emissions varies widely from unit to unit because processes, practices, and fuels all affect emission levels. For each fuel, several different processes are used for stationary combustion. Steam, hot water, and warm air furnaces are in common use for domestic heating and many specialized heaters are used by industry. Burners, combustion chambers, heat transfer characteristics, draft systems, and

Table 3–3.—COMMON USES OF VARIOUS FUEL-BURNING EQUIPMENT

Equipment	Common use
Coal-fired:	
Hand-stoked equipment	Residential, institutional, and commercial warm-air and boiler applications at capacities up to 5 million Btu per hour input. (Used primarily in coal-producing areas.)
Single-retort underfeed stokers	Residential, institutional, and commercial warm-air and boiler applications at capacities up to 40 million Btu per hour input.
Multiple-retort underfeed stokers Spreader stokers Traveling grate stokers Chain grate stokers Vibrating grate stokers	Water tube and fire tube boiler applications for institutional, commercial, and industrial heating at capacities in range of 5 million to 200 million Btu per hour input.
Pulverized-fuel-fired equipment (dry bottom or wet bottom)	Water tube boiler applications for power generation at capacities greater than 100 million Btu per hour input.
Oil-fired:	
High-pressure gun-type burners	Residential warm air furnace or boiler applications at capacities up to 3 gallons per hour distillate oil.
Low-pressure air-atomizing burners	Water tube and fire tube boiler applications for institutional, commercial, and industrial process heating with distillate or residual oil.
Rotary cup burners Steam atomizing burners High-pressure air-atomizing burners	Water tube and fire tube boiler applications for institutional, commercial, and industrial heating and power generation with residual oil.
Gas-fired:	
Premixing burners	Residential warm-air furnace or boiler applications and low-temperature industrial applications.
Nozzle mixing burners	Water tube and fire tube boiler applications for institutional, commercial, industrial, and power-generation applications. (May be combination type to permit fuel oil firing when gas supply is interrupted.)

Table 3-4.—ESTIMATED AMOUNT AND CONTROL STATUS FOR PARTICULATE EMISSIONS FROM STATIONARY COMBUSTION SOURCES IN 1966

Fuel and source	Uncontrolled emissions 10^6 tons [a]	Estimated control status in 1966,[b] percent	Estimated emissions in 1966	
			10^6 tons	Percent of total
Anthracite coal:				
Household and commercial	0.05	Negligible	0.05	1.1
Industrial	0.04	62.0	0.02	0.4
Power	0.17	86.5	0.02	0.4
Subtotal	0.26		0.09	1.9
Bituminous and lignite coal:				
Household and commercial	0.24	Negligible	0.24	5.4
Industrial	2.29	62.0	0.87	19.5
Power	21.14	86.5	2.85	64.1
Subtotal	23.67		3.96	89.0
Petroleum: [c]				
Household and commercial	0.08	Negligible	0.80	1.8
Industrial	0.17	Negligible	0.17	3.8
Power	0.03	Negligible	0.03	0.7
Subtotal	0.28		0.28	6.3
Natural gas:				
Household and commercial	0.06	Negligible	0.06	1.3
Industrial	0.05	Negligible	0.05	1.1
Power	0.02	Negligible	0.02	0.4
Subtotal	0.13		0.13	2.8
Grand total	24.34		4.46	100.0

[a] Basis for estimates:
1. Emission factors Table 5-1.
2. Energy consumption Table 3-2.
3. Fuel properties:
    - Anthracite coal—13,000 Btu/lb., 10 percent ash.
    - Bituminous coal—12,000 Btu/lb., 10 percent ash.
    - Distillate oil—140,000 Btu/gal.
    - Residual oil—150,000 Btu/gal.
    - Natural gas—1000 Btu/ft^3.

[b] Reference 15.

[c] Excludes naphtha, kerosene, range oil, and LP gas.

combustion controls of industrial heating units may vary widely. The practices of those responsible for selecting, installing, operating, and maintaining stationary combustion sources can also have significant effects on particulate emissions.

Because the rate of particulate emissions varies widely from unit to unit, the amount of particulate emissions that may be expected from a given source has not been established with accuracy. Data that are useful for estimating emissions from groups of units have been compiled and are reported as emission factors in Section 5.

3.3.2 Control Techniques

Techniques that will control particulate air pollution from stationary combustion sources may be broadly categorized as follows:

1. Gas cleaning
2. Energy substitution
3. Energy conservation
4. Good practice
5. Source shutdown

Although source relocation and dispersion techniques will not reduce particulate emissions from stationary combustion sources, they may effect some measure of improvement in ambient air quality in selected areas.

Table 3–5.—OPTIMUM EXPECTED PERFORMANCE OF VARIOUS TYPES OF GAS CLEANING SYSTEMS FOR STATIONARY COMBUSTION SOURCES

Sources	Removal of uncontrolled particulate emissions, percent						
	Systems in operation					Systems under development	
	Settling chambers	Large diameter cyclones	Small diameter cyclones	Electrostatic precipitators	Stack sprays	8-in. pressure drop scrubbers	Fabric filters
Coal-fired:							
Spreader, chain grate, and vibrating stokers.	50 [a]	60 [a]	85 [a]	99.5 [c]	60 [e]	99+ [g]	99.5 [h]
Other stokers	60 [a]	65 [a]	90 [a]	99.5 [c]	80 [e]	99+ [g]	99.5 [h]
Cyclone furnaces	10 [a]	15 [a]	70 [a]	99.5 [c]	(f)	(f)	(f)
Other pulverized coal units	20 [a]	30 [a]	80 [a]	99.5 [c]	(f)	99+ [g]	99.5 [h]
Oil-fired	5 [b]	10 [b]	30 [b]	75.0 [d]	(f)	(f)	(f)

[a] Estimate based on references 17 and 18.

[b] Efficiency estimated—not commonly used.

[c] Estimate based on reference 15.

[d] Estimate based on private reports of field experience.

[e] Reference 19.

[f] Insufficient data for estimate.

[g] Estimate based on reference 20.

[h] Estimate based on reference 21.

3.3.2.1 Gas Cleaning—Gas cleaning is the most common technique used for control of particulate emissions from stationary combustion sources. As shown in Table 3–4, 20 million tons of an estimated total of 24.5 million tons of particulate matter from stationary combustion was recovered by gas cleaning devices in 1966.

A wide variety of gas cleaning equipment is available for control of particulate emissions from stationary combustion sources. The cost of gas cleaning equipment is usually greater for devices of high efficiency; however, the performance of competitively priced gas cleaning equipment may differ considerably. Table 3–5 shows the optimum performance that may be expected from the various types of gas cleaning equipment that might be used for removing particulate matter from flue gases of stationary combustion sources. The efficiencies shown in Table 3–5 are estimates based on an analysis of information on particle size distribution, equipment efficiency, reports of experience from the field, and actual source tests.

More detailed information on the special application of these devices to stationary combustion sources is given in Section 4, Gas Cleaning Devices.

Settling chambers—The settling chamber is a low efficiency, low cost, low pressure drop gas cleaning device. Settling chambers are applied primarily to natural-draft, stocker-fired, coal-burning units. Collection efficiencies for this application are estimated to be 50 to 60 percent. Only a few oil-fired, gas-fired, and other coal-fired combustion sources are equipped with settling chambers.

Large-diameter cyclones—Large-diameter cyclones are more efficient than settling chambers, but have higher pressure drops. Efficiencies of large-diameter cyclones range from a high of 65 percent for some types of stoker-fired coal burning units to a low of 15 percent for coal-fired cyclone furnaces.

Multiple small-diameter cyclones—Multiple small-diameter cyclones are used on mechanical draft combustion units either as precleaners for electrostatic precipitators or as final cleaners. Efficiencies of well designed units range from 90 percent for some stoker-fired units to 70 percent for coal-fired cyclone furnaces.

Wet scrubbers—Sprays are used to a limited extent in the stacks of coal-fired units to control particulate emissions during soot blowing. The problems that limit the use of wet scrubbers include high corrosion rates, high or fluctuating pressure drops, adverse effects on stack gas dispersion, and waste disposal. Technically, these problems can be overcome, but the feasibility of wet scrubber systems for stationary combustion source particle control has not yet been demonstrated.

Wet scrubbers have been used experimentally for the removal of sulfur oxides from the flue gases of coal-fired sources. These scrubbers also removed combustion particulate matter with efficiencies of up to 99.5 percent.[20] A recently completed full-scale system connected to a pulverized coal-fired power plant boiler in Missouri is similar to the experimental installation. Evaluation of the economic feasibility and effectiveness of this system must be deferred until after shakedown runs are complete.

Electrostatic precipitators—Electrostatic precipitators are the most common gas cleaning devices used to remove particulates from the flue gases of large stationary combustion sources. Such devices are capable of collection efficiencies of at least 99.5 percent, and it is quite possible that even more efficient systems can be provided if necessary.[15] Electrostatic precipitator systems are usually applied to large pulverized coal-fired power boilers. The cost of these systems has limited their use on smaller combustion sources.

Electrostatic precipitators are highly sensitive, and if not properly designed, small changes in the properties of the particles and the gas stream can significantly affect their collection efficiencies.[22] Allowance should be made for possible changes in fuels, in fuel composition, and in gas temperature when consideration is given to the use of electrostatic precipitators. It has been established that low-sulfur fuels adversely affect the particulate collection efficiency of electrostatic precipitators designed for high-sulfur fuels.[23]

Fabric Filters—Fabric filters are not commonly applied to stationary combustion sources. Factors which limit the use of these devices are uncertainty of performance and reliability, and availability of other effective gas cleaning devices.

3.3.2.2 Source Relocation—Source relocation will not eliminate particulate emissions from stationary combustion sources, but it will eliminate emissions from the original location of the source. Due consideration should be given, however, to possible air pollution effects on other areas.

Source relocation is ordinarily considered when new stationary combustion sources are to be built, particularly when a new plant is to be built to replace one that has created air pollution problems.

3.3.2.3 Energy Substitution—The emission characteristics of fuels used in stationary combustion processes may differ widely. Therefore, some measure of control may be effected by substituting among the various fuels. Control of emissions may also be effected through the substitution of noncombustion energy for combustion energy. The substitutions considered in this section are limited to the more commonly used types of energy—hydraulic, electric, and nuclear—and fossil fuels. Fuels that might be considered as substitutes are LPG gas, coke oven gas, blast furnace gas, pipeline gas from coal, kerosene, range oil, coke oven tar, liquified coal, and low-ash coal. Although chemical, solar, and geothermal energies have long-range potential as substitutes that would reduce particulate emissions, these sources are not sufficiently developed to warrant current consideration.

Information on cost and availability of energy substitution is given in *Control Techniques for Sulfur Oxide Air Pollutants,* U.S. Department of Health, Education, and Welfare, 1969.

Power generation by stationary combustion is a principal source of particulate emissions in the United States (see Table 3–4). Energy sources used to generate power are water, nuclear fuel, gas, oil, and coal as shown in Table 3–6. Particulate emissions from gas- and oil-fired power plants total less than 0.1 pound per million Btu input. Coal-fired power plants equipped with gas cleaning devices that are 99.5 percent efficient compare favorably with oil- and gas-fired plants. Hydroelectric and nuclear power plants are particulate pollution free.

Substitutions commonly avilable for commercial, industrial, and domestic stationary combustion sources are electric power, coal,

Table 3-6.—COMPARISON OF ENERGY SUBSTITUTION ALTERNATIVES FOR ELECTRIC POWER GENERATION

Energy substitution alternative	Particulate emissions, lb/10^6 Btu input [a]
Hydroelectric	0
Nuclear	0
Gas (no control)	0.02
Oil (no control)	0.07
Coal—90 percent fly ash removal	0.67
Coal—99.5 percent fly ash removal	0.03

[a] Based on emission factors from Table 5-1 and the following gross heating values:
Coal—12,000 Btu/lb at 10 percent ash.
Oil—150,000 Btu/gal.
Gas—1,000 Btu/ft^3.

gas, and oil. Fossil fuels may be burned directly at the site where energy is used, or the fuels may be used to produce electrical energy for transmission to the site of use. Tables 3-7 and 3-8 compare the effectiveness of various substitution alternatives on the basis of particulate emissions per unit of useful heat.

When comparing substitiution alternatives, allowance should be made for differences in heat requirements between seemingly identical applications. The differences that might be found between fossil fuel and electrical heat requirements for space heating may be used as an example. Because electrically heated buildings are often insulated better than fossil fuel heating buildings, heat requirements may not be the same. It is recommended that individual studies be made to determine these differences by consulting with representatives of the fossil fuel, electrical, and building industries and by using information such as that published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers.[25]

To make comparisons for a given area, it it recommended that Tables 3-6, 3-7, and 3-8 be revised to reflect local conditions before substitution alternatives are compared.

Table 3-7.—COMPARISON OF ENERGY SUBSTITUTION ALTERNATIVES FOR STATIONARY COMBUSTION SOURCES OF LESS THAN 10 MILLION Btu/hr INPUT

Energy substitution alternative	Particulate emission equivalent [a] lb/10^6 Btu useful heat
Electric heat (hydroelectric or nuclear power plant originated)	0
Electric heat (gas-fired power plant originated)	0.05
Electric heat (oil-fired power plant originated)	0.22
Electric heat (coal-fired power plant originated—90 percent fly ash removal)	2.00
Electric heat (coal-fired power plant originated—99.5 percent fly ash removal)	0.10
Gas-fired furnace on site (no control)	0.03
Oil-fired furnace on site (no control)	0.08
Coal-fired furnace on site (no control)	1.11

[a] Based on:

1. Emission factors—Table 5-1.
2. Fuel properties:
   Heating value, coal—12,000 Btu/lb at 10 percent ash
   Heating value, oil—140,000 Btu/gal
   Heating value, gas—1,000 Btu/ft^3
3. Estimated thermal efficiency of on-site heating systems.
   Electric—100 percent
   Coal, gas, oil—75 percent
4. National average efficiency of power generation [24]—(Btu equivalent of generated power per unit of heat input).
   Coal—33.42 percent
   Gas—31.42 percent
   Oil—30.77 percent

Table 3-8.—COMPARISON OF ENERGY SUBSTITUTION ALTERNATIVES FOR STATIONARY COMBUSTION SOURCES OF 10 MILLION TO 100 MILLION Btu/hr INPUT

Energy substitution alternative	Particulate emission equivalent[a] lb/10^6 Btu useful heat
Electric heat (hydroelectric or nuclear power plant originated)	0
Electric heat (gas-fired power plant originated)	0.05
Electric heat (oil-fired power plant originated)	0.22
Electric heat (coal-fired power plant originated—90 percent fly ash removal)	2.00
Electric heat (coal-fired power plant originated—99.5 percent fly ash removal)	0.10
Gas-fired furnace on site (no control)	0.03
Distillate oil-fired furnace on site (no control)	0.14
Residual oil-fired furnace on site (no control)	0.20
Stoker-fired furnace on site (no control)	2.78
Stoker-fired furnace on site (90 percent fly ash removal)	0.28
Stoker-fired furnace on site (99.5 percent fly ash removal)	0.01

[a] Based on:

1. Emission factors—Table 5-1.
2. Fuel properties:
   Heating value, coal—12,000 Btu/lb at 10 percent ash
   Heating value, distillate oil—140,000 Btu/gal
   Heating value, residual oil—150,000 Btu/gal
   Heating value, gas—1,000 Btu/ft^3
3. Estimated thermal efficiency of on-site heating systems.
   Electric—100 percent
   Coal, gas, oil—75 percent
4. National average efficiency of power generation[24]—(Btu equivalent of generated power per unit of heat input).
   Coal—33.42 percent
   Gas—31.42 percent
   Oil—30.77 percent

Energy substitution can be an effective and useful technique for control of particulate emissions from stationary combustion sources. This technique has special value for control of many small sources when the cost of effective gas cleaning equipment would be excessive. When use of this technique is considered, attention should also be given to the effect of substitution on national security, foreign relations, industry, labor, commerce, conservation, and the public.

3.3.2.4 Energy Conservation—Energy conservation limits particulate emissions from stationary combustion sources by reducing fuel consumption. Energy conservation that is economical should be encouraged per se. Energy conservation that is not economical from the standpoint of individual process costs may actually be economical when compared with other techniques available for air pollution control.

Table 3-9.—TRENDS IN EFFICIENCY OF COAL, OIL, AND GAS USE IN UNITED STATES[24]

Year	Average Btu required to generate 1 (net) kw-hr		
	Coal	Oil	Gas
1956	11,257	12,828	12,245
1963	10,258	11,278	11,066
1964	10,241	11,138	10,962
1965	10,218	11,097	10,868

Improvement of power generation efficiency through use of high-temperature, high-pressure steam electric power generating processes reduces fuel consumption. Table 3-9 shows average national trends in efficiency improvement for steam electric power generating plants. Large, modern power plants with efficiencies near 8,000 Btu per kw-hr reduce energy consumption substantially to below the national average of 10,000 to 11,000 Btu per kw-hr, and processes now under development, such as the magnetohydrodynamic, electrogasdynamic, and fuel cell, have promise of improving efficiency even more.[26-28]

3.3.2.5 Good Practice—Equipment must be properly applied, installed, operated, and maintained to minimize emissions of particulate matter. Guidelines for good practice are published by the fuel industry, equipment manufacturers, engineering associations, and government agencies. Although improper practices are frequently the cause of visible particulate emissions, insufficient information exists to permit numerical evaluation of the effect of good practice on emission levels. Some sources of information on good practice are:

1. Air Pollution Control Association
2. American Boiler Manufacturers Association
3. American Gas Association
4. American Petroleum Institute
5. American Society of Heating, Refrigerating, and Air Conditioning Engineers
6. American Society of Mechanical Engineers
7. Edison Electrical Institute
8. Industrial Gas Cleaning Institute
9. The Institute of Boiler and Radiator Manufacturers
10. Mechanical Contractors Association of America
11. National Academy of Sciences—National Research Council
12. National Air Pollution Control Administration
13. National Coal Association
14. National Fire Protection Association
15. National Oil Fuel Institute
16. National Warm Air Heating and Air Conditioning Association
17. U.S. Bureau of Mines
18. Various State and local air pollution control agencies

Proper design and application—Combustion systems must be properly selected to meet load requirements. Components of the system should be compatible to avoid excessive emission of particulate matter.

Stationary combustion units are designed to operate within a specific range of load conditions. If such a unit is operated outside design limits, excessive discharge of particulate matter is possible. It is therefore necessary that the load be accurately estimated before stationary combustion systems are selected and applied. The total design capacity of the system should be sufficient to carry the maximum load, and consideration should be given to future increases in load requirements. The minimum design capacity of one unit of the combustion system should be sufficient to carry the minimum load requirements of the facility, and the total combustion system should be selected to carry, within design limits, any load between maximum and minimum.

Consideration must also be given to load characteristics when selecting a combustion system. The combustion system should be able to supply energy at a change in rate consistent with the demands of the facility without deviation from design limits.

Each component of the combustion system, such as the fuel handling system, the draft system, the fuel burning system, the flues and stacks, the ash handling system, and the controls related to these systems, must be properly selected and integrated to handle the load and the fuel to be burned.

Proper installation—Properly installed equipment will promote clean, efficient operation of stationary combustion sources. Comprehensive installation instructions and plans are a prerequisite for proper installation. The designer of the entire combustion system and the manufacturers of the system's components are responsible for providing such plans and instructions. Equipment should be installed only by qualified personnel, and all work should be inspected for quality.

Proper operation and maintenance—Proper operation and maintenance of stationary combustion equipment will promote the reduction of particulate air pollution. Stationary combustion units should be operated within their design limits at all times and according to the recommendations of either the manufacturer or another authority on proper operational practices. Combustion units and system components should be kept in good repair to conform with design specifications. Sensitive monitoring systems are helpful in indicating needed combustion system repair.

Proper operation also involves the reduction of emissions from fuel- and ash-handling systems. Storage pile fires and fuel- and ash-handling operations can become significant sources of particulate air pollution if good practice is disregarded.

3.3.2.6 Source Shutdown—Source shutdown is a drastic control technique, but it should not be completely disregarded. Source shutdown is useful for control of particulate emissions when air pollution levels threaten the public health in emergency episode situations and for control of emissions when lawful orders to abate are ignored.

3.3.2.7 Dispersion—Dispersion is discussed in detail in Section 6 of the report *Control Techniques for Sulfur Oxide Air Pollutants.*

3.4 INDUSTRIAL PROCESSES

3.4.1 Introduction

Approximately 6 million tons of dust, fume, and mist, were discharged from industrial processes and industrial fuels fired in 1966. This quantity would be considerably greater if high-efficiency collectors were not used by many industries. However, the total would be drastically lower if existing control technology were employed to the fullest.

Some industries inherently create more particulate air pollution than others, and for such industries one or two specific operations dominate the emission picture. In a given industry, particulate releases to the atmosphere are generally proportional to production rates. Often these discharges can be reduced dramatically through process changes or by the use of collection devices.

Table 3–10 lists many of the industries that release large quantities of particulate matter. As discharged, these particles include dry dusts, combustible oil and tar mists, inorganic acid mists, and combinations of these and other pollutants. The same processes frequently release gaseous pollutants, some of which may be more objectionable than the particulate matter. Although this discussion is limited to particulate matter, some remedial measures also affect sulfur oxides, odors, or other gaseous contaminants.

The industries which are cited in the following pages commonly use several types of fired heaters and boilers. Particulate emissions associated with this equipment, for the most part, are functions of the fuel burned. Combustion principles developed in Section 3.3 generally apply, and the combustion processes are not cited unless specific problems are associated with them.

3.4.2 Iron and Steel Mills

The major sources of particulate matter in iron and steel mills are blast furnaces, steelmaking furnaces, and sintering plants. Coke ovens, which are operated as adjuncts to steel mills, are discussed in Section 3.4.9.

3.4.2.1 Sintering Plants—Major sources of dust in sintering plants are the combustion gases drawn through the bed and the exhaust gases from sinter grinding, screening, and cooling operations.[40] Exhaust temperatures of the combustion gases range from 160° to 390° F. One 6000-ton-per-day plant operates at 350°F. About 50 percent by weight of the particles discharged from a sintering machine are larger than 100 microns.[29] Because dust generated in the sintering operation can be returned to the process, most plants are equipped with cyclones, which, because of the large particle size, usually operate at over 90 percent efficiency by weight. However, cyclone exit loadings range from 0.2 to 0.6 grains per cubic foot. High-efficiency baghouses and electrostatic precipitators, therefore, offer promise of much better collection. However, few have been applied to sintering machines.

3.4.2.2 Blast Furnaces—Iron ore, coke, and limestone are charged into a blast furnace to make iron. Under normal conditions the untreated gases from a blast furnace contain from 7 to 30 grains of dust per standard cubic foot (scf) of gas.[41] Most of the parti-

Table 3-10.—INDUSTRIAL PROCESS SUMMARY

Industry or process	Annual capacity, 1000 tons (except as noted)	Number of plants	Particulate emissions		Other emissions	Reference
			Nature	Principal sources		
Iron and steel mills	149,000	184	Iron oxide dust, smoke	Blast furnaces, steel making furnaces, sintering machines.	CO, combustion products	29, 30
Gray iron foundries	17,350	1,400	Iron oxide dust, smoke, oil and grease, metal fumes.	Cupolas, shakeout systems, core making.	Odors, combustion products, hydrocarbons from contaminated scrap.	31, 32
Non-ferrous smelters	2,721	2,500	Smoke, metal fumes, oil and grease.	Smelting and melting furnaces	SO_x combustion products	31, 33
Petroleum refineries and asphalt blowing.	3,650 x 10^6 bbls.[a]	318	Catalyst dust, ash, sulfuric acid mist, liquid aerosols.	Catalyst regenerator, sludge incineration, air blowing of asphalt.	Hydrocarbons, SO_x, H_2S, odors.	31, 34
Portland cement	500 x 10^6 bbls.[b]	180	Alkali and product dusts	Kilns, coolers, dryers, material handling systems.	Combustion products	31, 35
Kraft pulp mills	30,000	88	Chemical dusts, mists	Chemical reclaiming furnaces, smelt tanks lime kilns.	Odors, SO_x	36
Asphalt batch plants	----	----	Aggregate dusts	Dryers, material handling systems.	Odors, combustion products	----
Acid manufacture:						
Phosphoric	2,300	66	Acid mist, dust	Thermal processes—phosphate rock acidulating, grinding and handling system.		
Sulfuric	20,513	223	Acid mist		HF, SO_x, odors	37
Coke manufacturing	54,278	60	Coal and coke dusts, coal tars.	Charging and discharging oven cells, quenching, material handling.	Phenols, H_2S	29
Glass furnaces and glass fiber manufacture.	----	----	Sulfuric acid mist, raw material dusts, alkaline oxides, resin aerosols.	Raw material handling, glass furnaces, glass fiber forming and curing.	Combustion products	----
Coffee processing	----	----	Chaff, oil aerosols, ash dehydrated coffee dusts.	Roasters, spray dryers, waste heat boilers, coolers, stoners, conveying equipment, chaff burning.		38
Cotton ginning	----	----	Cotton fiber, dust and smoke.	Gins, trash incineration	Defoliants and insecticides	39
Carbon black	1,496	37	Carbon black	Carbon black generators	----	
Soap and detergent manufacturing.	----	----	Detergent dusts	Spray dryers, product and raw material handling systems.	Combustion products, odors	----
Gypsum processing	----	----	Product dusts	Calciners, dryers, grinding and material handling systems.	Combustion products	----
Coal cleaning	----	----	Coal dusts	Washed coal dryers	Combustion products	----

[a] Barrel = 42 gallons.

[b] Barrel = 376 pounds.

cles are larger than 50 microns in diameter. The dust contains about 30 percent iron, 15 percent carbon, 10 percent silicon dioxide, and small amounts of aluminum oxide, manganese oxide, calcium oxide, and other materials. Blast furnace gas cleaning systems normally reduce particulate loading to less than 0.01 grain per standard cubic feet to prevent fouling of the stoves where the gas is burned. These systems are composed of settling chambers, low efficiency wet scrubbers, and high efficiency wet scrubbers or electrostatic precipitators connected in series.

3.4.2.3 Steel Furnaces—The three most important types of steel-making furnaces are open hearth furnaces, basic oxygen furnaces, and electric furnaces. Relative usage as a percent of total production of each of these furnaces in 1958, 1966, and 1967 is shown in Table 3–11.

Table 3–11.—STEEL PRODUCTION, PERCENTAGE BY PROCESS[42]

Furnace type	Percent of total		
	1958	1966	1967
Open hearth	90.7	72.1	55.6
Basic oxygen	1.5	17.4	32.6
Electric	7.8	10.5	11.8

Average emission rate from a hot-metal open-hearth furnace is about 0.4 grain per scf for a conventional furnace and 1.0 for an oxygen-lanced furnace.[43, 44] Up to 90 percent of the particles are iron oxide, predominantly FE_2O_3. A composite of particles collected throughout a heat show that about 50 percent were less than 5 microns in size. Control of iron oxide requires high-efficiency collection equipment such as venturi scrubbers and electrostatic precipitators. Because of the cost involved and the growing obsolescence of open hearth furnaces, industry has been reluctant to invest money in the required control equipment.[44] Often these furnaces have been replaced by controlled basic oxygen furnaces and electric furnaces.

More emissions are created by the basic oxygen furnace than by the open-hearth furnace. The principal portion of the increase in emissions is caused from furnace oxygen blowing. Emissions of about 5 grains per scf are reported as typical.[45] Particle size is small; 85 percent are smaller than one micron in diameter.[46] All basic oxygen furnaces in the United States are equipped with high-efficiency electrostatic precipitators or venturi scrubbers.

Electric furnaces are usually used for alloy production, and because of their flexibility, are becoming popular for most metal melting operations. Emissions from electric furnaces often reach particulate matter concentrations of 3 grains per scf. Only 40 to 50 percent of the dust is iron oxide, an amount considerably smaller than that emitted by other furnaces. The particles are difficult to collect because of a strong tendency to adhere to fabric surfaces, a high angle of repose, and a high electrical resistivity, and because they are difficult to wet. Approximately 70 percent by weight of the particles are smaller than five microns and 95 percent by number are smaller than 0.5 micron in diameter.[47] Nevertheless, except for difficulties inherent in the charging operation, over 95 percent effective collection can be achieved with appropriate hooding and high-efficiency collection equipment. Baghouses are especially suited for such collection.

3.4.3 Gray Iron Foundries

Melting cupolas are the principle sources of particulate matter at iron foundries. Casting shake-out systems, sand handling systems, grinding and deburring operations, and coke-baking ovens are other sources.

Cupola exhaust gases are hot and voluminous, and contain significant portions of combustible matter and inorganic ash. The most effective control system incorporates an afterburner to eliminate combustibles and a fabric filter to collect the inorganic dust and fume. Coolers must be used ahead of the baghouse to protect fabric filters from the heat of the exhaust gas. Most such systems use glass fabrics, but some synthetic cloths have been found to be satisfactory. Even though baghouse control systems provide excellent particle collection, they have not met with wide acceptance, principally because of cost.[48] Dry centrifugal collectors and scrubbers with various efficiencies are used in many instances. High-efficiency scrubbers are reported to provide about the same performance as fabric filters, but visible emissions are more pronounced.

Casting shake-out and sand cleaning are dusty operations that are normally well controlled. For these operations baghouses are commonly used; medium-efficiency scrubbers and dry centrifugal collectors are also used.

Core ovens create relatively smaller quantities of particulate matter, much of which is in the form of finely divided liquid aerosols. Emissions from core ovens are similar to those discharged from paint baking and resin curing operations with odors being more objectionable than the particulates. A properly designed afterburner will eliminate most of the particulates and malodors.

3.4.4 Petroleum Refineries

Major sources of particulate matter at refineries are catalyst regenerators, airblown asphalt stills, and sludge burners. Lesser sources include fired heaters, boilers, and emergency flares.

In modern fluidized catalytic crackers, fine catalysts are circulated through the reactor and regenerator vessels. From 100,000 to 150,000 cfm of hot, dusty gases are vented from a large regenerator. Dust collectors as well as carbon monoxide waste heat boilers are often used to control air pollution. It is common practice to install a carbon monoxide boiler to use the fuel value of the clean gas stream exiting from the particulate collector.

In typical installations 2-stage or 3-stage cyclones are located in the regenerator vessels of FCC units for catalyst recovery and reutilization. In some cases external cyclones are installed to reduce the particulate content of the flue gases leaving the regenerators of these units. Catalyst dust losses from the regenerator equipped with internal cyclones and in some cases supplemented by external cyclone equipment can range in the order of 100 to 350 pounds per hour depending on the size, age, and basis of design of the unit.

Electrostatic precipitators may also be used to collect the fine particles from the regenerator exit gases and some refiners have reported catalyst dust losses as low as 40–60 pounds per hour although typical current installations have higher emission rates. The percent efficiency of the precipitators is a function of the inlet dust loading from the regenerator and the desired emission rate to the atmosphere.

Airblowing of asphalts generates oil and tar mists and malodorous gaseous pollutants. It is common practice to scrub the oils and tars from the hot (300 to 400°F) gas stream. Sea water is sometimes used for this purpose. In any case, separators are necessary to reclaim the oil and prevent contamination of effluent water. Afterburners are used to incinerate the uncondensed gases and vapors, which can constitute an odor nuisance.

As petroleum refineries, the open burning or incineration of sludges can be a major source of particulate matter and sulfur dioxide emissions. These sludges are a mixture of heavy petroleum residues and such inorganic materials as clay, sand, and acids. Because the materials cannot be separated readily, sludge is usually atomized in much the same way as heavy fuel oil. The organic fraction can be burned effectively in such an incinerator, but any inorganic matter is entrained in exhaust gases. High-efficiency precipitators, baghouses, and high-energy scrubbers are among the stack cleaning devices that are available to collect the fine dusts; the final choice of control unit would be based upon the nature of the sludge. Sulfur dioxide collection would not be effected. However, if there is an accessible sulfuric acid plant, sludge may be conditioned and used as part of the acid plant's feed material. Very low grade sludges may be dumped at sea. It must be emphasized that incineration alone is not the solution for the disposal of all forms of refinery waste sludges. Solvent extraction is another method for recovering the organic fraction and the separated "clean" solids are acceptable to normal landfill sites.

3.4.5 Portland Cement

Both mining of raw materials and manufacture of cement create dust. Dust is generated at the blasthole drilling operation at the quarry, during blasting at the rock face, and during loading of trucks. At primary and secondary crushing plants, in the grinding mills, at blending and transfer points, and in the final bagfilling and bulk truck or railroad car loading operations, where the particulate-laden air is at ambient temperatures, bag filters are usually the best means of control.[49]

Rotary dryers used in dry process cement plants may be a major source of dust generation and require collecting systems designed for higher temperatures. Dust concentrations of 5 to 10 grains per scf entering the collector are normal. Baghouses or combinations of multiple cyclones and baghouses are frequently used. Newer dry process cement plants incorporate the drying operation into the raw grinding circuit. In such a "dry-in-the-mill" combination drying and grinding circuit dusts are normally vented to a baghouse.

The largest sources of emissions at cement plants are direct-fired kilns for burning Portland cement clinker. Exit gas particulate loadings are usually 5 to 10 grains per scf for wet kilns and 10 to 20 grains per scf for dry-process kilns. Exhaust gases from wet-process kilns contain considerably more moisture than gases from dry process kilns. The volume of the hot (500° to 600° F) kiln gases may exceed 250,000 cubic feet per minute. Over 85 percent by weight of gasborne particles are smaller than 20 microns in diameter. The most prevalent chemical constituents are calcium oxide (CaO), about 41 percent; silicon dioxide (SiO_2), 19 percent; and aluminum and iron oxides (Al_2O_3+Fe_2O_3), 9 percent. The balance would be predominately CO_2.[50]

Electrostatic precipitators are widely used to control particulate emissions from kilns. Fabric filters of siliconized glass bags have been installed on both wet and dry process kilns. Each control device has been successful when adequately designed and properly maintained.

3.4.6 Kraft Pulp Mills

The major source of particulate emissions in kraft pulping is the recovery furnace in which spent cooking liquors are burned to remove the organic materials dissolved from the wood to recover the inorganic cooking chemicals. Sodium sulfate is the major chemical released as particulate matter. Small amounts of sodium carbonate, salt, and silica, and traces of lime, iron oxide, alumina, and potash also are emitted. Because 95 to 98 percent of the total alkali charged to the digester finds its way to the spent liquor, it is economically imperative that it be recovered.

Electrostatic precipitators of about 90 percent efficiency are used to recover particles emitted from recovery furnaces. New installations call for design efficiencies of about 97.5 percent, and at least one such unit has a design efficiency of over 99.9 percent.

Other sources of particulate matter are smelt tanks and lime kilns. Stack dust from lime kilns can be collected in 85 to 90 percent efficient venturi scrubbers. Water sprays of 20 to 30 percent efficiency and mesh demisters of 80 to 90 percent efficiency are usually used on smelt tanks.

3.4.7 Asphalt Batching Plants

Hot asphalt batching plants are potential sources of heavy dust emissions.

Asphalt batching involves the mixing of hot, dry sand, aggregate, and mineral dust with hot asphalt. Although conveyors and elevators generate some dust, the major source is the direct-fired dryer used to dry and heat aggregates. Exit gases range from 250° to 350° at volume rates of 15,000 to 60,000 standard cubic feet per minute (scfm). Most dryers employ simple cyclone separators which collect 70 to 90 percent of the dust entrained in the exit gases. Nevertheless, the remaining dust in the gas stream usually totals more than 1000 pounds per hour and further dust controls are needed in most areas.

Centrifugal and baffled scrubbers have been used with success in many areas to control the fine dust which escapes the primary cyclone. High efficiencies are reported—some exceed 99.0 percent—with losses from most tested plants ranging from 20 to 40 pounds per hour. It is common to vent elevators and major conveyor transfer points to the scrubber.[51]

As high temperature fabrics were developed, fabric filters found greater acceptance at asphalt batch plants. Such filters have been used successfully at asphalt batch plants since 1950. Recently, several were installed in Chicago, Illinois, in an effort to obtain better dust control than had been afforded with scrubbers. They are reported to provide excellent collection of fine particles with little or no visible emissions from the baghouse. Although fabric filters frequently are more expensive than scrubbers, they collect dry "fines" which may be useable in high-grade asphaltic concrete mixes. In addition, they obviate the need for holding ponds and preclude water problems.

3.4.8 Acid Manufacture

Most of the particulate matter attributed to acid manufacture is created in the production of sulfuric and phosphoric acids. Manufacture of the other two major industrial acids—nitric and hydrochloric—does not generate large amounts of acid mist.

3.4.8.1 Sulfuric Acid — Over 90 percent of the sulfuric acid in the United States is manufactured by the contact process.[37] In the process sulfur or other sulfur bearing materials are burned to sulfur dioxide (SO_2) and catalytically converted to sulfur trioxide (SO_3). Uncontrolled emissions range from 0.05 to 0.23 grain per scf of exit gas. Concentrations depend to a large degree on plant design and proper operation of the acid absorber. Most modern plants are equipped with high-efficiency electrostatic precipitators or mesh eliminators in which 99 percent of the acid mist is recovered. Acid mists are usually controlled to a far greater extent than gaseous SO_2 releases.

The primary source of emissions in the chamber process is the final Gay Lussac tower. Combined sulfuric acid mist and spray in the exit gas ranges from 0.08 to 0.46 grain per scf.

3.4.8.2 Phosphoric Acid — Two processes are used to manufacture phosphoric acid. High-purity acid for the food and detergent industries is produced by burning elemental phosphorous. The process is similar to the contact sulfuric acid process. The oxidation product, phosphorous pentoxide (P_2O_5), is hydrated and absorbed in phosphoric acid. Mist is collected from exhaust gases with electrostatic precipitators or high pressure drop mesh entrainment separators. Acid mists escaping collection are extremely hygroscopic so that visible emissions are pronounced unless high collection efficiencies are achieved. High-purity phosphorous for this process is manufactured in electric furnaces, which create gaseous fluorine compounds and solid particulates.

The wet process is used to produce less pure phosphoric acid for the fertilizer industry. During the manufacturing process, sulfuric acid is reacted with phosphate rock. Except for material handling and grinding operations few particulates are generated. However, the acidulation reaction liberates large quantities of gaseous silicon tetrafluoride (SiF_4), and scrubbers are required.

3.4.9 Coke Manufacture

Metallurgical coke is the solid material remaining after distillation of certain coals. About 90 percent of the United States coke output is used for production of blast furnace iron.

Conventional coking is done in long rows of slot-type coke ovens into which coal is charged through holes in the top of the ovens. Coke oven gas or other suitable fuel is burned in the flues surrounding the ovens, to furnish heat for coking. Flue temperature is about 2600° F and the coking period averages 17 to 18 hours. At the end of the coking period, incandescent coke is pushed out of the furnace into quenching cars and carried to a quenching station, where it is cooled with water sprays.

The beehive oven is a simpler type of coking oven. Distillation products from this oven are not recovered. Its use has diminished with the development of the byproduct oven. The process persists because of an economic advantage during peak production periods. Capital investment is lower and inoperative periods can be tolerated. About 1.5 percent of the total coal coked in 1967 was produced in these ovens. A very large part, i.e., 25 to 30 percent of the coal charged to these ovens is emitted to the atmosphere as gases and particulate matter. Ducting these emissions to an afterburner appears to be a feasible method of control.

Coal and coke dust emissions result from coal car unloading, coal storage, crushing and screening, the coking process (where the largest releases of particulate dust occur during larry car coal charging of the byproduct oven and pushing of the product coke to quench cars), quenching, and final dumping from the quench car.

Slot type coke ovens currently being designed include the following features that speed operations and minimize leaks:

1. Better designed and thinner-walled heating flues to improve heat transfer and minimize cool spots and undercoking. This results in a cleaner pushing operation.
2. Improved refractories, with less spalling and cracking. These refractory defects cause warping of metal furnace parts, gas leaks into flue systems and chimneys, and voids which fill with undercoked coal and cause smoke during pushing.
3. Gas-tight, self-sealing oven doors, that minimize manual sealing with clay.
4. Mechanical cleaners or self-sealers for doors and for top-charging hole covers. A few grains of sand on a metal seat can cause appreciable leakage of hot gases.
5. Sealing sleeves for leveling bars. Leveling bars are used to even out the oven charge to allow free passage of gas over the charge into the gas collector main.
6. Mechanical removal of top coal-charging lids and means to charge all three holes of an individual oven rapidly and simultaneously, with gas recovery mains in operation.
7. Steam jet aspirators in byproduct header ducts.
8. Anintercell header to normalize the cell pressure throughout the battery.
9. Charging car volumetric sleeves and dust entrainment chutes.
10. Wooden baffling to separate particulate matter from quench tower effluent gases.

A breakthrough in coke manufacturing technology is needed to improve operations.[52] Improvements have been slow.[53] Installations exist that have employed supposedly superior charging and discharging equipment, but satisfactory operations have not been achieved. A joint research effort by several steel companies has been under way for 5 years to develop new coke manufacturing technology, but potential commercial applications appear to be five years away.[53]

Another form of coke, used in blast furnace refractories and in the manufacturing of electrodes for large steel and aluminum reduction furnaces, is calcined petroleum coke. Petroleum coke is a refinery product, but is seldom calcined by the refinery. Calcining occurs in a rotary kiln at 1700° F removing absorbed water and heavy oil and forming a marble-size product. Volatilized hydrocarbons are usually passed to a 2200° F combustion chamber before being released to the atmosphere. Subsequent conveyance of the dusty product to the storage requires hooding and enclosed ducting. The dust is abrasive and causes heavy wear on bucket elevators and other transfer equipment. Control of particulate matter can be accomplished during loading of the coke. One system uses concentric tubing; the inner filling tube carries the coke and the outer tube exhausts entrained dust from the enclosed railroad car, truck or ship hold. Baghouses are used to capture dust from loading as well as dust generated at other handling and transfer points.

3.4.10 Primary and Secondary Recovery of Copper, Lead, Zinc, and Aluminum

Primary smelting of lead and zinc involves converting the sulfide of the ore to an oxide through roasting, and subsequent reduction of the metal oxide to its metallic state in a separate vessel. Copper, however, requires a preliminary smelting step, during which the naturally occurring complex sulfide is reduced to the cuprous sulfide, CuS_2, by mixing the charge with limestone. The cuprous sulfide is then converted to blister copper in a converter where the sulfur is removed by oxidation. Sulfur dioxide gas is released from these operations, along with particulate matter which is largely sublimed oxides, dust, and acid mists. When sulfur dioxide emissions exceed 3 percent of these furnace exhaust volumes, a sulfuric acid manufacturing plant is feasible. Pretreatment of the smelter gases going to the acid is required to remove particulate matter. If sulfur dioxide recovery is not practiced, fiberglass demisters or precipitators are usually used to remove particulate material from smelter exhaust gases. For a more detailed discussion of smelting, refer to the report *Control Techniques for Sulfur Oxide Air Pollutants.*

Most materials fed to secondary recovery furnaces are alloys of copper, zinc, tin, or lead in the form of solid scrap and drosses. Gases from the furnaces may contain as fumes oxides of the low boiling metals. Particularly bothersome are submicron lead and zinc fume. Zinc oxide fume particle size ranges from a high of 0.5 micron to a low of 0.03 micron. Baghouses are usually used to control these oxide fumes; where the fumes are corrosive, electrostatic precipitators are used. Soiled scrap metal melting may evolve grease or oil fumes as smoke during the heatup phase. Incineration of the smoke with a control afterburner is necessary if the metal cannot be cleaned before melting.

Metallic aluminum is produced by the electrolytic reduction of alumina (Al_2O_3) in a bath of fused cryolite by the Hall-Heroult process. Cell operating temperatures range from 1700° to 1800° F. The gases generated in the cells are corrosive and toxic, and consist of hydrogen fluoride and volatilized fluorides. Some fine particulate matter is entrained in the exit gases. Water scrubbers have long been used for collection of both the particulate and corrosive gases. Some installations have used baghouses with alumina coated cloth filter bags.[54]

Secondary aluminum recovery operations produce particulate matter from the fluxes used, from impurities in the scrap, and from chlorination of the molten aluminum. Oily or greasy scrap gives off smoke. When chlorine gas is used to degas the melt or remove magnesium, hydrogen chloride gas and aluminum chloride fume are evolved. The fume is difficult to collect because of its small particle size and hygroscopic nature. Water scrubbers are used to collect the gaseous contaminants.

3.4.11 Soap and Synthetic Detergent Manufacture

Principal sources of particulate matter in the making of soap and synthetic detergents are the spray drying of products and the handling of dry raw materials. The wet chemical processes used to make soaps and detergents are relatively innocuous from the particulate standpoint, although malodorous gases and vapors are generated in some instances.

Gases from the spray dryers, discharged at approximately 200° F, contain large amounts of moisture. In addition, the product is sticky at these temperatures so that dry collection in fabric filters or electrostatic precipitators is difficult. Multiple cyclones may be employed as precleaners, but scrubbers are used almost exclusively to collect fine dust. Moderate pressure venturi units or baffled scrubbers provide adequate control in many instances. These scrubbers usually use slurries rather than merely water and product is recovered from the slurries. Residual fine particles, together with high moisture levels, frequently impart marked opaqueness to the stack gases. It is sometimes possible to avoid this problem by adding some of the less stable ingredients to the product after the spray drying operation.

Fabric filters are widely used in soap and detergent plants to control dusts generated from the handling of products and raw materials and from packaging operations.

3.4.12 Glass Furnaces and Glass Fiber Manufacture

Reverberatory furnaces are used to produce nearly all glass products. The furnaces and raw materials generate significant quantities of particulate matter.

Glass furnaces are usually heated with oil or natural gas, which is fired directly over the melt. Heat is reclaimed in checkerwork regenerators used to preheat combustion air. Raw materials are charged at one end of the furnace and molted glass is pulled from the other end. Cullet (scrap glass), limestone, soda ash, and sand are the main ingredients fed to the furnace melter section. Glass temperatures are as high as 2700° F in the furnace, but are usually near 2200° F at the point of discharge. Particulate matter in exhaust gases is traceable to two principal sources: (1) Fine raw materials that are entrained in combustion gases before they are melted; and (2) Materials from the melt, such as sulfur trioxide created by sulfate decomposition and other solids picked up by escaping carbon dioxide gases. Sulfur trioxide and the oxides of potassium, sodium, and calcium are the main constituents of particulate emissions. Losses from large furnaces range from less than 10 pounds per hour to as high as 100 pounds per hour. Most units release less than 40 pounds per hour. Particulate releases tend to be affected by feeder designs and the makeup of raw materials.

Operators control emissions through furnace design, electric heating, and raw material control rather than with stack cleaning devices. Control of emissions with fiberglass filters is feasible, but the particulate matter is extremely difficult to handle.

In the manufacture of glass fiber, the emissions from the forming processes are considered unacceptable both from the standpoint of odor and visible particles. Although suitable control methods are not at hand, it appears that a combination of process changes and stack controls will be required to render exit gases acceptable in many communities. These methods are being developed and prospects are good that satisfactory techniques will be found. Afterburners have been employed with success at curing ovens where volumes are low in comparison to forming lines.

3.4.13 Carbon Black

Because of the extremely fine size (0.01 to 0.4 micron) and fluffy nature of carbon black particles, they are readily emitted from improper handling and transferring operations and during separation of them from the process gases. Emissions have been particularly heavy from channel black process plants. The furnace black process (oil and gas) accounts for 94 percent of the total production and technology is available to control emissions from these plants.

Furnace temperature is kept at about 2500° F and the black-laden gases are cooled to 450° and 550° F before entering the dust collecting equipment. The preferred system consists of an agglomerator followed by a baghouse.[39] Coated fiberglass bags last about 12 months. The over-all particulate collection efficiency of such a system is about 99 percent. The combination of cyclone and electrostatic precipitator is no longer satisfactory because it collects only about 60 percent of the particulate matter.

3.4.14 Gypsum Processing

Gypsum, the basic ingredient of plaster and wallboard, is manufactured by grinding, drying, and calcining gypsum rock. At most plants much of the gypsum is processed into wallboard in highly mechanized systems. Grinding, drying, and calcining processes are principal sources of dust. Handling, packaging, and wallboard manufacture are of secondary potential.

Most grinding operations are controlled with fabric filters. Fine grinders often are equipped with built-in pneumatic conveyors that allow the product to be collected in the filter.

Gypsum is dried in direct-fired dryers to remove free moisture before calcining. Exit gases of about 220° F contain a large amount of fine dust. Electrostatic precipitators, baghouses, or scrubbers are almost always used to remove this dust from exit gases.

The calcining operation is conducted at 400° to 450° F in externally heated kettles or conveyors. In general, exit gases from the calcining operation are less voluminous than those from dryers. Historically, electrostatic precipitators have been used to control calciners. Dust collection has not always been adequate, and baghouses now find better acceptance. Most new gypsum plants have been equipped with fabric filters. High-temperature fabrics are required and heaters have to be installed to prevent moisture from condensing in duct work.

Baghouses are used extensively in modern gypsum plants to collect dust from various conveying and processing points. In most instances a salable product is reclaimed.

3.4.15 Coffee Processing

The processing of green coffee beans and the production of dehydrated instant coffee generate dust and liquid aerosols as well as odorous gases. The most prominent sources are roasters, spray dryers, waste heat boilers, and green coffee cleaners.

Roasters are the predominant sources of oil aerosols and odors but also create significant amounts of solid particulate matter. Chaff, a flaky membrane from the bean, and other solids are collected in simple cyclones at temperatures of 400° to 500° F. Remaining aerosols and odorous gases may be incinerated in afterburners at temperatures ranging from 1200° to 1400° F.

Coolers and stoners create additional solid particulate matter, but few aerosols or malodors. Cyclones normally provide adequate dust control. With some continuous systems, the exit of roaster gases through close coupled coolers requires the use of afterburners on the cooler exhaust stream.

Spray dryers not unlike those used in other industries are used to produce instant coffee. If the dryer is operated properly, very little fine particulate matter is generated and satisfactory dust control can be achieved with dry multiple-cyclone collectors. Periodic excursions can be expected with resultant discharges of fine dust. Many plants operate scrubbers or baghouses downstream of mechanical collectors. Collected fines are blended with the main product stream. Dust recovered in dry collectors is of sufficient value to make it attractive to maintain collector efficiencies.

At instant coffee plants, large quantities of leached coffee grounds are produced. Many operators burn the spent grounds in waste heat boilers similar to coal-fired boilers. Particulate emissions are dependent on the type of firing and the ash content (usually about 4 percent by weight of dry grounds). A common design incorporates an underfeed stoker and auxiliary gas burners.

Green coffee cleaning and handling creates dust and chaff which normally can be handled well in simple cyclones.

3.4.16 Cotton Ginning

The major sources of particulate matter in cotton ginning are the gin itself and the subsequent incineration of the trash. Relatively coarse materials are emitted from the ginning operation and relatively fine materials escape the associated lint cleaner. High-efficiency multiple-cyclones successfully collect the coarse particles, and the recently developed stainless steel in-line filter is effective on the fine particles.

Disposal of the cotton trash by composting, rather than incineration, is being practiced in some parts of the country. Incineration of trash generates a large portion of the particulate matter released from uncontrolled ginning plants.

3.5 CONSTRUCTION AND DEMOLITION

3.5.1 Introduction

The demolition and construction of buildings and roads creates particulate air pollution with periodic emissions characteristically dependent on the specific operations. The handling of dusty materials, movement of trucks on temporary roads, and breaking of masonry walls are a few of the more prominent dust generating operations. None is continuous and the dust from almost all can be reduced if suitable procedures are used.

Principal demolition, construction, and related operations that generate particulate air pollution are:

1. Demolition of masonry.

2. Open burning of wooden structures, trees, shrubbery, and construction lumber.
3. Movement of vehicles on unpaved roads.
4. Grading of earth.
5. Paving of roads and parking lots.
6. Handling and batching of Portland cement, plaster, and similar materials at the site.
7. Sandblasting of buildings.
8. Spray painting of exposed surfaces.

Essentially all of these processes generate particulates that create local nuisances. Techniques have been developed to minimize dust releases from most offending operations; however, none of these are entirely satisfactory. Furthermore, all of the control measures require some expense and attention and offer little, if any, monetary return.

3.5.2 Demolition of Masonry

When a brick, plaster or concrete wall is demolished, most of the particulate matter is released when the broken wall hits the ground or floor. In urban areas, water sprays are used to keep exposed surfaces as wet as possible. Before walls are torn down they are sprayed with water, and as the debris crashes to the ground more water is sprayed onto the pile. The procedure at best is inefficient and as it is ordinarily practiced may reduce particulate matter by only 10 to 20 percent. In cold or freezing weather, water spraying systems become almost completely inoperable.

One concept of dust collection at demolition sites calls for enclosing the four sides of the building by means of plastic sheets attached to the scaffolding by removable clips.[55] The top of the building is left open and air is sucked in by a large exhaust fan into bag filters for collection. As yet this concept has not been applied. Nevertheless, it offers one of the few possibilities for adequate collection of demolition dust in congested metropolitan areas.

3.5.3 Open Burning

Because open burning cannot be controlled adequately, the only solution is to stop the practice and remove wood and other combustibles to an incinerator or sanitary landfill or to handle it in some other acceptable manner.

3.5.4 Road Dust

Trucks moving across dry, unpaved roads are a prime dust source at construction projects. Dust can be held to a tolerable level by blacktopping or at least oiling such surfaces. For very temporary roads, frequent spraying with water may be satisfactory.

3.5.5 Grading Roads and Other Surfaces

There are few satisfactory remedies for dust created by earth-moving equipment. It is best to conduct such operations when winds are light and materials are sufficiently moist to minimize entrainment of dust in ambient air currents. Sand, rock, gravel, and the roadbed can be sprayed with water.

3.5.6 Handling Dusty Materials

Portland cement, plaster, and similar items are easily rendered airborne during handling and batching. If the materials are mixed at the site, greater possibilities are presented for the evolution of dust. The best approach is to mix such materials in a central location, hooding all major points and venting the dust to a fabric filter.

3.5.7 Sandblasting

The cleaning of stone and concrete surfaces by sandblasting creates particles that are difficult to control by common techniques. When access is possible, hooding and ductwork can be provided from the point of sandblasting to a baghouse or similar high-efficiency dust collection device. A more common practice has been to shroud the operator and the area being cleaned. Most of the resultant dust is contained within the canvas shroud and drops to the ground below. A clean air supply has to be piped by hose to the operator. The arrangement is successful when winds are light. Under strong wind velocities much of the particulate matter remains airborne. Sandblasting of buildings has been replaced in many areas by steam cleaning and acid washing.

3.6 SOLID WASTE DISPOSAL

3.6.1 Introduction

Disposal of solid wastes contributes to air and water pollution and threatens to pollute the land (through improper disposal methods). In 1967, 190 million tons of solid wastes were collected excluding some industrial and agricultural sources.[56] Of this quantity, 86 percent was disposed of at land disposal sites, 8 percent was burned in municipal incinerators, and only 6 percent was disposed of in what could truly be called a sanitary landfill.[56] Much of the waste in disposal sites is ultimately burned in the open. Emissions from these activities represent the most frequent cause of local air pollution complaints by citizens.[57] Particulate emissions from incineration cause soiling, visibility reduction, and a generally unsanitary appearance of the air.

Better engineering and planning are required to cope with the problem of disposing of solid wastes in a manner that will least affect our environment. One survey indicates that if present trends continue and long-range plans are not made and implemented, this country will not have the capability to handle the increased amount of solid wastes generated in the year 1975.[58] Planning, perhaps on a regional basis, and proper use of existing technology, specifically in the fields of incineration and sanitary landfill operation, are the key to mastering the problem of air pollution from solid waste disposal.

3.6.2 Definition of Solid Waste

As defined in the Solid Waste Disposal Act of 1965, "The term 'solid waste' means garbage, refuse, and other discarded solid materials, including solid-waste materials resulting from industrial, commercial, and agricultural operations, and from community activities, but does not include solids or dissolved material in domestic sewage or other significant pollutants in water resources. . ." It includes both combustibles and non-combustibles, such as garbage, rubbish, ashes, street refuse, dead animals, and abandoned automobiles. Solid waste is grouped into the following five categories:[59]

1. Residential and commercial solid waste. Food waste, paper, plastics, metals, cloth, wood, and numerous other materials are included in residential and commercial solid waste. Heating value is approximately 4500 Btu per pound. Uncompacted density is approximately 250 pounds per cubic yard—compacted density is approximately 500 pounds per cubic yard.

2. Construction and demolition waste. This category includes building materials such as wood, steel, plaster, brick, and concrete.

3. Institutional solid waste. Wastes from hospitals, nursing homes, and other institutions are included in institutional solid waste. Such wastes are similar to residential and commercial solid wastes, but may contain pathogenic materials.

4. Industrial solid waste. Waste products as produced by industry include a variety of combustible and non-combustible materials.

5. Agricultural waste. Agricultural waste includes animal droppings and crop residue, but does not include stands of timber or brush burned as a result of accidental forest fires. Reference articles on agricultural waste disposal may be found in Section 8, Bibliography, under the heading of Food and Argicultural Sources.

3.6.3 Amounts of Solid Waste Generated

The amount of solid waste generated in this country is truly astronomical. Altogether, 190 million tons per year or 5.3 pounds per person per day are collected.[56] A breakdown of this latter figure is shown in Table 3–12. These figures however, are only for that amount of waste actually col-

Table 3-12.—AVERAGE SOLID WASTE COLLECTED [56]

[Pounds per person per day]

Solid wastes	Urban	Rural	National
Household	1.26	0.72	1.14
Commercial	0.46	0.11	0.38
Combined	2.63	2.60	2.63
Industrial	0.65	0.37	0.59
Demolition, construction	0.23	0.02	0.18
Street and alley	0.11	0.03	0.09
Miscellaneous	0.38	0.08	0.31
TOTALS	5.72	3.93	5.32

lected. Other amounts are also generated beyond that collected and these amounts are best described in the following quotation from Reference 56.

> "It must be recalled that 10 to 15 percent of household and commercial wastes are collected or transported by the individual generating the waste. Approximately 30 to 40 percent of the industrial wastes are self-collected and transported. Additionally, local regulations—or lack of them—permit over 50 percent of our population to burn some type of household waste in their backyards. About 45 percent of commercial and other establishments are also allowed to practice controlled open burning of some type. Thus, although the amount of waste material that has to be collected is staggering in itself, the amount of material that is actually generated and could pose potential collection problems is even more impressive. Conservative estimates indicate that 7 pounds of household, commercial, and municipal wastes are presently generated per person per day; this totals over 250 million tons per year. To this must be added our estimate of over 3 pounds per person per day for industrial wastes, amounting to an additional 110 million tons per year. Thus, estimates for 1967 indicate that over 10 pounds of household, commercial, and industrial wastes are being generated per day in this country for every man, woman, and child, totalling over 360 million tons per year.[56]
>
> "To these figures we must add over 550 million tons per year of agricultural waste and crop residues, approximately 1.5 billion tons per year of animal wastes, and over 1.1 billion tons of mineral wastes. Altogether, over 3.5 billion tons of solid wastes are generated in this nation every year. [56]

3.6.3.1 Disposal Methods to Minimize Air Pollution—Many areas of the country have adequate land available for sanitary landfills. A properly operated sanitary landfill in which solid waste is buried daily without burning can turn a worthless piece of property into a valuable recreation area. The cost of a landfill operation, in most cases, is less than incineration, not considering hauling costs in either case.[60] Expanded use of landfills, of course, may require an efficient municipal pick-up system. At present, only about 6 percent of municipal solid waste, not including industrial and agricultural waste, is disposed of in a sanitary landfill. [56]

Some solid wastes such as automobile bodies, paper and wood chips have a salvage value or reclamation potential. If a market exists in an area for part of all of the waste currently being burned, it can be developed and used to reduce or eliminate air pollution. Frequent collection of municipal refuse and the pickup of leaves in the fall will deter the citizen from open burning. Disposal methods other than combustion are, in many cases, economical. These methods can be put to use, however, only with the execution of adequate planning.

In metropolitan areas in which land is becoming scarce for landfill operations, combustion processes are being used to reduce refuse volume by as much as 90 percent before disposal in a landfill, increasing the life expectancy of the landfill site. [61] Incineration is often used to sterilize pathogenic or contaminated waste and reduce its volume before burial. Our expanding society may have to resort to more extensive incineration in many areas as an alternative to landfill.[62]

Of the total amount of municipal solid waste produced, not counting agricultural or industrial solid waste, 86 percent is ultimately disposed of in open dumps where open burning is frequently practiced.[56] Such methods of volume reduction normally do not meet health and esthetic standards that usually are desired by a progressive community,[63] because of the large amount of particulate matter (as much as 16 pounds per ton of solid waste burned) released to the atmosphere with virtually no possibility of controlling emissions.[1] Open burning has been banned in at least six States.[65]

Even today many apartment house, commercial, and municipal incinerators being built do not meet requirements of good air pollution control standards. Some incinerators can operate with a minimum of air pollution; however, these units are costly to operate and maintain, and if poorly operated will create noticeable air pollution. The trend today is toward multiple-chamber incinerators of adequate design that are equipped with efficient control devices and full instrumentation as well as towards controlled municipal size units. Municipal units now proposed in this country are of the water-wall type that produce steam as a saleable product and collect more than 99 percent of the particulate matter emitted from the incinerator itself by means of electrostatic precipitators.

3.6.3.2 Disposal Methods Without Incineration—Disposal and volume-reduction methods that do not use incineration are most desirable from an air pollution standpoint. In many cases they may be more economical and may prove to be more acceptable to a community than methods using incineration.

Sanitary landfill—The sanitary landfill, which should not be confused with an open dump, is an acceptable means of solid waste disposal.[66] Almost any kind of material can be disposed of by this method of systematically dumping solid waste on the ground or in trenches, compacting the waste by driving a bulldozer or other heavy equipment over it, and covering the waste at the end of each day with a layer of compacted earth to prevent rodent and insect infestation and to confine odors. When completely filled, land so used may be made into parks and recreation areas. A properly operated sanitary landfill is operated without open burning. Air pollution emissions are limited to material entrained in the air by earth-moving equipment. Even these emissions, however, can be kept to a minimum by wetting the fill material.

Choice of a site and method of operation of a sanitary landfill is essentially dependent on the topography and availability of land. In addition, other factors such as length of haul, land drainage, source of cover material, and quantity of land needed to handle future waste generation must be considered before choosing a final site. Some factors that must be considered are:

1. Land requirements. About 1 acre-foot of land is required for each 1000 persons for one year operation when the production of waste is 4.5 pounds per day per capita.[67] In addition, cover material totaling at least 20 percent by volume of the compacted waste is required. Such material may be supplied from the site or transported from nearby areas. Normally, sites are designed for 10- to 20-year service periods.
2. Topography. Depressed areas such as ravines and abandoned pits where the grade must be raised are usually considered desirable for sanitary landfill sites. Flat land can be used by applying progressive excavation or the cut and cover method of operation.[66]
3. Operation. Proper operation of a sanitary landfill requires continuous use of heavy earthmoving equipment to compact and cover the waste with fill material. It is essential that waste be covered by no less than a 6-inch layer of material at least once a day. An intermediate layer of cover material (about 1 foot deep) is usually spread over completed sections of the site. An additional 2 feet of final cover is required as a

minimum for the entire site on completion of the operation.

4. Cost. Costs of site, site preparation, and operation must be computed to judge the true cost of sanitary landfill operation. In addition, the final value of the land when reclaimed must be balanced against the initial cost of the land. Sanitary landfill equipment and operating costs usually range from $0.80 to $1.50 per ton of solid waste placed in the landfill.[68] (Transportation of waste to the site is not included in this figure.)

Composting—Composting, as applied to waste disposal, is the biological decomposition of the organic component of waste. Stable organic residue is the ultimate product. The residue is usable as low-grade soil conditioner. The market for compost, however, has not been very good, because equivalent commercial products are available at less cost.

Composting requires separation of nonorganic material from the waste. To be economical, a market for such scrap is necessary.

Composting costs are the same or higher than those of incineration. Consequently, only a few plants are operating in the United States today.[69] Actually, however, in the case of a composting plant operated by a municipality, there is no more reason to expect such a plant to be profitable than an incinerator, as both perform essentially the same service for the citizens of the municipality: that of getting rid of solid wastes. In areas where commercial fertilizer is not readily available and the scrap market is good, composting could be a suitable method for handling organic wastes with little or no particulate air pollution. However, some compost plants have odor problems.

Shredding—Disposal of bulky waste can be facilitated by shredding. Auto tires, for instance, can be shredded and placed in a sanitary landfill instead of being burned. Bulky wood waste, such as driftwood and combustible demolition waste, which has heretofore been burned openly because of the difficulty of incinerating it, can be shredded and incinerated in a conventional incinerator provided it is mixed with conventional refuse so that it does not blind the grates. It can also be disposed of in a landfill site.

Each year more than six million automobiles are junked in the United States. Automobile body disposal, therefore, is one of the growing solid waste problems. The most promising solution to the problem appears to be to step up the reuse for autobody metal scrap in the domestic steel and foundry industry, so that the large portion of the available supply now being discarded each year can be remelted.

Air pollution arising from disposal of automobile bodies results, however, when they are burned to remove upholstery, grease, and paint. Such burning is apparently required to produce a useable scrap that is competitive with other available material. Open burning of automobile bodies has proven entirely unacceptable from an air pollution standpoint. Large quantities of particulate matter are generated by such burning. Metallic particles containing cadmium, nickel, and lead may also be released by this method of disposal.

Open burning of junk automobiles has been replaced by controlled incineration in enclosures.[70] Emissions from such practices have been successfully controlled by afterburners, wet scrubbers, and electrostatic precipitators. Unfortunately, however, because of the low market price paid for automobile scrap, the cost of purchasing, operating, and maintaining such control equipment is prohibitive in many areas. It would appear therefore, that these control techniques need to be reapplied, perhaps in conjunction with process changes, to lower operating and maintenance costs, and allow the higher installation costs resulting from more sophisticated designs to be amortized over the life of the installation. Such designs might attempt to minimize inlet air flow so that the control devices could be made as small and inexpensive as possible.[71] Also, where afterburners are used, heat recovery might be considered.

A possible solution to the air pollution problem is the expanded use of mechanical devices which can disintegrate and shred a whole car (minus the block, rear axle, and seats), remove contaminants by a series of mechanical separations, and produce a relatively useable scrap with little or no incineration.[72] Such processes can be used by most larger cities. Cost of equipment for a unit capable of handling from 200 to 300 cars per day is $500,000. Cost for a unit capable of handling 1200 cars per day ranges from $1 million to $3 million.[73]

In many locations, however, the low market price paid for shredded scrap has restricted the area from which shredders can draw junk auto-bodies. Although it, too, is restricted by low scrap prices, the practice of flattening junk autos and delivering them from outlying areas to a centralized shredder results in some cars being processed without generating as much air pollution as if they were burned in the open.

Compaction—Compaction, although not a disposal method, has the potential of reducing on-site refuse volume to a point that large storage areas are not required and transfer to final disposal at landfills or municipal incinerators is easier. Compaction devices are now being marketed for installation in larger apartment complexes. In some instances, these units have replaced chute-fed incinerators.

Compaction installations are similar to chute-fed incinerator installations. Normally, refuse is charged by tenants through a door located on each floor of the building. Refuse builds up to a predetermined level in a receiving hopper, usually in the basement, then is forced by hydraulic ram into a storage container or bag. Compaction of refuse in the storage container is claimed to be accomplished up to 3 to 1. Recent investigations indicate, however, that much higher compaction ratios may be obtained.

Metal containers with capactities up to two cubic yards have been used. It has been reported that one container is required for every fifty apartments, with removal two to five times per week.

Installed cost of a compactor is reported to be $3500, plus $175 per floor for the metal chute. Hauling cost of the compacted refuse for a 100-unit apartment building in one area of the country is $85 per month. Incineration of the same refuse would cost $50.

Widespread use of compaction units could place a heavy burden on pickup and disposal facilities of a municipality and could cause an accumulation of refuse should scheduled pick up be prevented. Another disadvantage of such a disposal method is the high cost of installing such units in older buildings.

3.6.3.3 Disposal Methods With Incineration—Incineration, as a means of volume reduction, may be justified in areas where land for sanitary landfill is scarce or hauling costs are prohibitive. That well designed and well operated equipment be used to minimize the discharge of particulate matter to the atmosphere is of utmost importance in the use of incinerators.

Emissions of particulate air pollutants from combustion of solid waste, including open burning, can range from 3 to 28 pounds per ton of refuse, depending on the degree of combustion and control of emissions.[1] Reduction of these emissions to the desired level requires either that the incinerator be designed for control of fly ash or that a separate control system be used. Table 3-13 summarizes the collection efficiency of various control devices when applied to incinerators.

Table 3-13.—MAXIMUM DEMONSTRATED COLLECTION EFFICIENCY OF INCINERATOR CONTROL EQUIPMENT[74, 75]

Collection device	Collection efficiency, percent
Settling chamber	35
Wetted baffles	53
Cyclones	75 to 80
Impaction scrubbers (with pressure drop less than ten inches of water)	94 to 96
Electrostatic precipitators	99+
Bag filters	99+

Open burning—The results of the National Solid Wastes Survey show that open burning is widespread. Eighty-six percent of the 190 million tons of solid waste collected in 1967 went into land disposal sites, 75 percent of which resulted in some form of open burning.[56] The Bureau of Solid

Waste Management of the Environmental Control Administration sees even a higher percentage of the sites as undesirable as indicated by the following quotation:

> "This country has over 12,000 land disposal sites being utilized by collection services, control of 94 percent of which is unacceptable and represents disease potential, threat of pollution, and land blight. By no stretch of the imagination do these sites resemble a sanitary landfill. The waste management field must face the challenge of studying and evaluating these sites to determine their suitability for conversion to sanitary landfills. We must develop the necessary plans, finances, and action programs to convert those sites that can function as a sanitary landfill. In many instances it will be necessary to close and abandon many of these sites. Local government then must locate and develop new sites for immediate use now and to provide necessary capacities for the increase of the future.[56]
>
> "To eliminate open dumps, and the air pollution that results from open burning in them, as well as other environmental pollution, may cost as much as $230 million per year for 5 years.[56] This represents about 5 percent more than is currently being spent annually for solid waste management."[56]

Open Top Incinerators—A refractory-lined rectangular chamber with a full, open top and forced overfire air has been used to incinerate a variety of wastes including liquids, solids with high caloric value,[76] general trash, and municipal refuse. This design, because of its relatively low cost, has been applied to waste disposal by both municipalities and industries. Tests of a pilot unit conducted by the National Air Pollution Control Administration have shown excessive particulate emissions for high-ash materials and for low-ash materials under certain operating conditions. Low emissions were realized for a low-ash (0.5 percent by weight) material incinerated under carefully controlled conditions.[77] Operation of full-scale units on certain high-Btu low-ash wastes are being conducted without visible emissions of smoke, but no quantitative test data are yet available. Before applying this technique, careful consideration should be given to the ash content and physical characteristics of the waste, and tests should be conducted on the specific waste. As with all combustion sources, this type of unit requires control of charging and air flow to prevent the emission of smoke and excessive fly ash. All installations should be equipped with appropriate instrumentation to ensure operation within allowable air pollution limits. Additional tests are contemplated to further define significant parameters which can be used to estimate performance on any waste material.

Conical metal burners—Conical metal waste burners are used in the lumber industry to incinerate wood wastes. This single-chamber incinerator is not properly designed to minimize atmospheric emissions, and is usually not operated or maintained properly. Consequently, large amounts of particulate matter are emitted from such units. Some areas of the country, in fact, have banned all new construction of these burners. Conical metal burners are not satisfactory for other types of refuse either. [78]

Domestic Incinerators—Domestic incinerators may include such units as single-chamber backyard units with no auxiliary fuel to dual chamber incinerators having a primary burner section followed by an afterburner section.

Many air pollution control agencies have banned installation and use of backyard incinerators. A few air pollution agencies have in the past prohibited the installation of some or all types of domestic incinerators because of the inability to meet various local standards pertaining to emissions of particulates, organic compounds, or odors. Such action may be due in part to excessive emissions caused by negligent operation of such units and the fact they can be operated without using the gas burners.

Commercial and industrial incinerators—Commercial and industrial incinerators for burning general refuse range in capacity from 50 to several thousand pounds of refuse per hour. These units may be classified into two general designs, single- and multiple-chamber incinerators. A single-chamber unit is so designed that admission, combustion, and exhaust to a stack take place in one chamber. The multiple-chamber incinerator has separate chambers for admission and combustion of the solid refuse, mixing and further combustion of the fly ash and gaseous emissions, and settling and collecting of the fly ash. Industrial wastes other than general refuse require special designs based on characteristics of the particular waste.

Single-chamber incinerators have generally proven inadequate to meet most emission regulations. Emissions from such units have been reported to be as much as 10 pounds of particulate matter per ton of refuse burned.[1] Multiple-chamber incinerators, however, when designed, operated, and maintained properly, reduce the volume of refuse sufficiently and produce a minimum of particulate emission. Emissions from such units have been reported to be as little as 3 pounds per ton of refuse burned.[1] Even well-designed multiple-chamber incinerators may require a good gas washer to meet more stringent regulations. The National Air Pollution Control Administration has tentatively found that scrubbers having at least ½ inch H_2O pressure drop and a water rate of 4 gallons per 1,000 scfm are required for Federal incinerators to meet emission standards for Federal facilities.[79]

To keep particulate emissions to a minimum, design standards for any incinerator must include means to satisfy the following criteria:[80]

1. Air and fuel must be in proper proportion.
2. Air and fuel must be mixed adequately.
3. Temperature must be sufficient for combustion for both the solid fuel and gaseous products.
4. Furnace volume must be large enough to provide the retention time needed for complete combustion.
5. Furnace proportions must be such that ignition temperatures are maintained and fly ash entrainment is minimized.

Even an incinerator of proper design must be operated and maintained properly to minimize particulate emissions. Where charging and operation cannot be closely supervised, scrubbers and auxiliary burners can minimize emissions. Periodic cleaning and adjustment of burners, spray nozzles, fans, and other appurtenant devices are also necessary to minimize emissions.

Initial incinerator cost depends mainly on the capacity of the unit and the degree of air pollution control desired. Figure 3-2[81] shows typical costs for incinerators without scrubbers, with low-efficiency scrubbers, and with high-efficiency scrubbers. Presumably, these costs data are for the approximate time the information was presented, December 1966. To meet the most stringent emission standards and to minimize visible emissions and fly ash, most incinerators must be equipped with scrubbers.

Design criteria and operating practices previously described for general refuse incinerators should also apply to units burn-

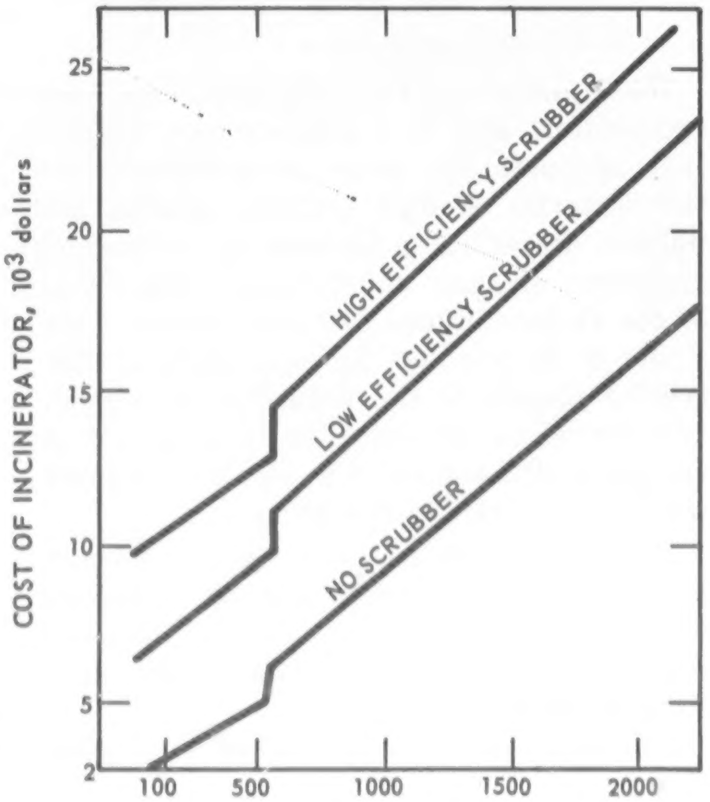

FIGURE 3-2. Cost of incinerator at three levels of control of particuate emissions.

ing pathological waste. Primary factors that affect particulate emissions from pathological incinerators include:

1. Gas burner rates should be sufficient to maintain at least 1400° F in secondary chamber.
2. Burner placement should be such that all waste in primary chamber is covered by flame from burner.
3. Preheating should be accomplished with secondary burners prior to charging of waste.

Many air pollution control agencies review on a routine basis all plans for future incinerator installations to ensure that these units meet emission standards. Details that are usually checked in such a review include:

1. Plot plans to see if unit is located in a suitable area.
2. Unit capacity to see if it is adequate for the expected daily waste generation.
3. Gas burner placement and fuel rates.
4. Scrubber water flow rate.
5. Materials of construction for resistance to heat, stress, and corrosion.
6. Air port sizes.

Recognizing the fact that emissions from incinerators are, to a great extent, a function of operation, some air pollution control agencies conduct training courses and publish literature to be used by incinerator operators or their supervisors. Once aware of the factors influencing atmospheric emissions, it is possible for operators to contribute greatly to the reduction of particulate emissions by such simple practices as regularly cleaning out the ash pit or preheating the unit prior to operation.

Apartment house incinerators—Apartment house incinerators are an important pollutant source in urban areas of the country. Smoke and fly ash from these units cause many complaints.

Emissions are usually higher than other incineration systems because of low combustion temperatures and improper air regulation. Adequate control of this source in most cases has not been achieved, although stricter air pollution regulations are inspiring the application of new control measures.

The most common apartment house incinerator is the flue-fed or single-flue, single-chamber model. In this unit refuse is charged down the same passage that the products of combustion use to leave the unit. Refuse dropped onto the fuel bed during burning smothers the fire and causes incomplete combustion. Improvements in design have been made to the single-flue, single-chamber unit. There are now chute fed units that are multiple-chamber incinerators with separate passages for the refuse and products of combustion. This design provides improved combustion and air regulation but emissions would still exceed most emission standards. Inherent in the design of flue or chute-fed models is the high natural draft in the flues of a tall apartment building which is a major cause of high particulate emissions.

Air pollution agencies have approached the control of these units in different ways. New York has prohibited the installation of new apartment house incinerators and has issued specific criteria for upgrading existing units. Washington, D. C., and Atlanta do not allow flue or chute-fed units to be installed. Detroit and Philadelphia have set emission standards at a level that requires efficient collection equipment, usually water scrubbers, on apartment house incinerators.

In upgrading existing units and designing new units, several techniques are used to overcome the problems of excessive emissions from apartment house incinerators. A gate at the base of the charging chute is used to prevent refuse from entering the incinerator during burning and to prevent the products of combustion from leaving through the charging flue. This approach is preferable to locking the hopper doors be-

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cause these locks eventually either fail on their own or are broken by occupants of the building. For single-flue units, a bypass or separate flue must be constructed for the products of combustion. Auxiliary burners are placed in the primary and/or secondary chambers of the incinerator to increase burning temperature and improve combustion.[82]

Draft control has been used in New York to reduce entrainment of fuel bed material in the effluent gas stream. A sensor is placed in the primary chamber to monitor draft. When a preset draft level is exceeded a damper located in the breeching at the incinerator outlet is activated and decreases the amount of air entering the incinerator.

An important step is the addition of efficient gas scrubbers to the incineration system. Scrubbers designed to increase the velocity of the gases and contact them with low-velocity water appear to be preferable to spray nozzle units because plugged nozzles reduce collection efficiency. A final improvement is the establishment of definite burning periods. Burning cycles depend on the relative size of the apartment house and incinerator, and are quite variable. The intent of such cycles is to systematically destroy the refuse without overloading the incinerator, and to minimize smoldering refuse by destroying all waste charged during any one cycle. Employment of the above techniques should reduce emissions to a level of 2 to 6 pounds per ton of refuse burned.[83]

Municipal incinerators—In 1966, 254 municipal-size incinerators were in operation in the United States. The average capacity of these units is 300 tons per day. Most installations are old (70 percent were installed before 1960) and not designed to minimize air pollution.

"It is estimated that approximately $150 million is required to construct new incinerators for replacement of existing inadequate incinerators and conical burners. An additional $75 million is required for air pollution control equipment to upgrade or replace existing inadequate incinerators."[56]

Approximately 8 percent of all municipal solid waste, not including agricultural and industrial waste, is burned in municipal incinerators.[56]

Design criteria for municipal incinerators—Municipal incinerators may be classified as either batch-fed or continuously fed units. Continuously fed units are preferable because operating parameters, such as combustion chamber temperatures that affect particulate emissions, can be closely controlled. Grates must be of proper design to ensure complete burnout of material. At the same time, however, grates should mix or tumble the refuse as gently as possible to minimize entrainment of material in the exhaust gas.

Most municipal incinerators in this country are of the refractory-lined furnace type. Water-wall furnaces are more common in Europe. This type of unit offers the advantage of steam generation. As a consequence of heat recovery in the steam generation process, flue gas temperatures are lower than those of refractory-lined units. Lower flue gas temperatures cause smaller flue gas volumes, which in turn require smaller, less costly air pollution control equipment. In addition, water-wall units can be operated with less excess air, which further reduces stack gas volume.

Air pollution control equipment—Most municipal incinerators in the United States are equipped with some form of fly ash control system. Generally, this system consists of a simple baffle-type spray chamber. These spray chambers prevent hot cinders and large particles from being emitted to the atmosphere, but they do not effectively control finer material.

More efficient collection devices will be required for municipal incinerators to meet reasonable air pollution control codes. The medium pressure drop (6 inches of water) scrubber and the electrostatic precipitator are two control devices capable of effective particulate control. No precipitator has yet been installed on any American municipal incinerator, but several have been installed and successfully operated in Europe. Several devices with collection efficiencies of over 95 percent are scheduled for new and existing units.[84] High efficiency scrubbers, in contrast to precipitators, might also control emissions of potentially odorous and toxic gas.

Cost of municipal incineration and control devices—Current costs of constructing municipal incinerators may range from $6,000 to $13,000 per ton of rated 24 hour capacity.[85] Costs in the low end of the range represent incinerators of relatively simple design with minimal controls, such as a settling chamber. Costs for incinerators of complex design, equipped with sophisticated controls such as electrostatic precipitators, would be near the high end of the range. Between 30 and 40 percent of this cost is usually spent on operating equipment and the remainder is spent on building and land. Operating costs (not including plant amortization) range from $4 to $8 per ton of refuse incinerated.[84] Precipitator (95 percent efficiency) cost for two 250-ton-per-day incinerators is reported at approximately $430,000.[86]

3.6.4 Air Pollution Potential From Solid Disposal Methods

There are approximately 12,000 land disposal sites in this country.[56] Such sites may be defined as locations, either privately or publicly owned, on which there is dumping of solid wastes by public or private contractors. Only 6 percent of these sites may be termed sanitary landfills, in that they have daily cover, no open burning, and no water pollution problems.[56] On three-quarters of the remaining 94 percent of the land disposal sites, some form of open burning is practiced.[56] This type of ultimate disposal accounts for a large share of the particulate emissions estimated to arise from the burning of solid wastes.

Some amounts of construction, institutional, industrial and agricultural waste are also burned. Emissions from field burning to remove weeds or residue, incineration of wood waste, and burning of car bodies for salvage can contribute significantly to local and even regional air pollution problems. In some areas of the country these sources may, in fact, be the greatest cause of particulate air pollution.

3.6.5 Public Health Service Programs and Assistance in Solid Waste Disposal

With passage of the Solid Waste Act of 1965, the Federal Government made a commitment to support and assist in a coordinated national effort to solve solid waste problems.[87] The Solid Wastes Program of the Environmental Control Administration presently supplies technical and financial assistance relating to methods for handling solid wastes. The National Air Pollution Control Administration also provides technical assistance on air pollution emissions and control techniques for solid waste disposal methods. Public Health Service regional office directors should be contacted in regard to specific services available. In addition, where problems of solid waste disposal arise in connection with mining industries, the Solid Waste Research Group of the Bureau of Mines may also be consulted.

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4. GAS CLEANING DEVICES

4.1 INTRODUCTION

Gas streams contaminated with particulate matter may be cleaned before the gas is discharged to the atmosphere. Gas cleaning devices take advantage of certain physical, chemical, and/or electrical properties of the particulate matter and gas stream. Selection of a gas cleaning device will be influenced by the efficiency required, nature of the process gas to be cleaned, characteristics of the particulate and gas stream, cost of the device's use, availability of space, and power and water requirements. Other basic considerations include maintenance, dependability, and waste disposal. It has been estimated that total expenditures in 1966 of industrial air pollution control equipment in the United States were about $235 million.[1] Value of shipments of the industrial gas cleaning equipment industry in 1967 was double the 1963 figure, and the backlog of orders recently nearly equalled a year's productive output. Undoubtedly legislative pressure and local pollution control regulations have supplied the impetus for such rapid growth in this industry.[2] Table 4–1 shows an up-to-date list of the types and values of control equipment being sold to various industries.[2]

This chapter discusses the wide array of commercially available gas cleaning devices and summarizes published operating characteristics, including efficiencies, and information that will help determine the gas cleaning devices suited for a specific application. Information presented includes:

1. Introductory material (definitions and theoretical principles).
2. Equipment description and design (variations, arrangements, and performance).
3. Typical applications (including efficiency data).
4. Operational factors (power requirements, pressure drops, temperature

Table 4–1.—MANUFACTURERS' SHIPMENTS OF INDUSTRIAL GAS CLEANING EQUIPMENT BY END USE IN 1967

[Thousands of dollars]

	Electrostatic precipitators	Fabric filters	Mechanical collectors	Scrubbers particulate	Scrubbers gaseous	Gas incinerators and adsorbers	Total shipments
Iron and steel	5,783	4,536	2,300	7,423	4,275	(b)	24,317 [b]
Utilities	15,506	(a)	2,476	(a)	(a)	(a)	18,481
Chemicals	1,207	5,344	3,130	3,709	1,479	1,001	15,870
Rock products [c]	2,760	3,602	1,038	1,142	(a)	(a)	8,966
Pulp and paper	(a)	122	802	989	193	(a)	6,753
Mining and metallurgical	(a)	1,855	389	825	394	(a)	6,160
Refinery	(a)	(a)	(a)	(a)	(a)	282	4,098
All other [d]	687	4,959	8,408	3,901	114	2,137	20,206
Exports	(a)	1,081	(a)	651	72	79	5,744
Total shipments	36,509	21,730	22,381	19,229	6,770	3,976	110,595

[a] Not published to avoid disclosure.

[b] Gas incinerators and adsorbers purchased by iron and steel companies are included in "all others" category to avoid disclosure.

[c] "Rock products" includes cement and asbestos plants.

[d] "All other" includes shipments to distributors where end use cannot be identified.

limitations, corrosion and maintenance problems, and waste disposal).

Cost factors for each major type of control device are discussed in Section 6 of this report. Capital, installation, and operating costs are provided for settling chambers, cyclones, scrubbers, electrostatic precipitators, fabric filters, and afterburners.

4.1.1 Preliminary Selection of Equipment

The selection of gas cleaning equipment is far from an exact science and must be based on particle and carrier gas characteristics, and process, operating, construction, and economic factors.

Important particle characteristics consist of size distribution, shape, density, and such physio-chemical properties as hygroscopicity, agglomerating tendency, corrosiveness, "stickiness", flowability, electrical conductivity, flammability, and toxicity.[3]

Test methods for determining some of the properties of fine particulate matter cited above are outlined in the American Society of Mechanical Engineers' Power Test Code Number 28.

The process factors affecting selection of a gas cleaner are volumetric flow rate, variability of gas flow, particle concentration, allowable pressure drop, product quality requirements, and the required collection efficiency. Required collection efficiency is based on the value of the material being collected, the nuisance or damage potential of the material, the physical location of the exhaust, the geographical location (i.e., the air pollution susceptibility of the area), and present and future local codes and ordinances.

Ease of maintenance and the need for continuity of operation are operating factors which should be considered. Important construction factors include available floor space and headroom and construction material limitations imposed by the temperature, pressure, and/or corrosiveness of the exhaust stream. Economic factors consist of installation, operating, and maintenance costs.

Information on the particle size gradation in the inlet gas stream is very important in the proper selection of gas cleaning equipment. Particles larger than 50 microns may be removed in inertial and cyclone separators and simple, low-energy wet scrubbers. Particles smaller than 50 microns require either high-efficiency (high-energy) wet scrubbers, fabric filters, or electrostatic precipitators.[4]

Wet collectors operate at variable efficiencies directly proportional to the energy expended and can handle changing effluent flow rates and characteristics. Disadvantages of wet scrubbers are (1) scrubber liquor may require treatment, (2) power cost is high, and (3) a visible plume may be emitted. Fabric filters more readily permit reuse of the collected material and can collect combustible and explosive dusts. They do, however, have temperature limitations and are sensitive to process conditions. Electrostatic precipitators can operate at relatively high temperatures, have low pressure drop, low power requirements, and few moving parts. They are, however, sensitive to variable dust loadings or flow rates and, in some cases, require special safety precautions.

The performance of various gas cleaning devices may differ widely depending upon the particular application. Grade efficiency curves for selected gas cleaning devices are shown in Figure 4– as an illustration of a method for describing collection equipment performance for one application.[5,6] The performance of the various gas cleaning devices shown could differ significantly for other applications.

As a further aid in the selection of particulate matter collection equipment, the areas of application of the various cleaning devices are given in Table 4–2.[1] Other areas of application have been summarized at the end of each equipment section. The reader should refer to those sections and to the material referenced therein.

4.2 SETTLING CHAMBERS

4.2.1 Introduction

Gravitational settling chambers use the force of gravity to separate dusts and mists from gas streams. Such collectors are simple in design and operation, but have low collection efficiency. The principal disad-

Table 4-2.—USE OF PARTICULATE COLLECTORS BY INDUSTRY[1]

Industrial classification	Process	EP	MC	FF	WS	Other
Utilities and industrial power plants	Coal	0	0	----	----	----
	Oil	0	0	----	----	----
	Natural gas	----	----	----	----	----
	Lignite	0	0	----	----	----
	Wood and bark	+	0	----	+	----
	Bagasse	----	0	----	----	----
	Fluid coke	0	+	----	----	+
Pulp and paper	Kraft	0	----	----	0	----
	Soda	0	----	----	0	----
	Lime kiln	----	----	----	0	----
	Chemical	----	----	----	0	----
	Dissolver tank vents	----	0	----	----	+
Rock products	Cement	0	0	0	+	----
	Phosphate	0	0	0	0	----
	Gypsum	0	0	0	0	----
	Alumina	0	0	0	+	----
	Lime	0	0	+	----	----
	Bauxite	0	0	----	----	----
	Magnesium oxide	+	+	----	----	----
Steel	Blast furnace	0	----	----	0	+
	Open hearth	0	----	----	+	+
	Basic oxygen furnace	0	----	----	0	----
	Electric furnace	+	----	0	0	----
	Sintering	0	0	----	----	----
	Coke ovens	0	----	----	----	+
	Ore roasters	0	0	----	+	----
	Cupola	+	----	+	0	----
	Pyrites roaster	0	0	----	0	----

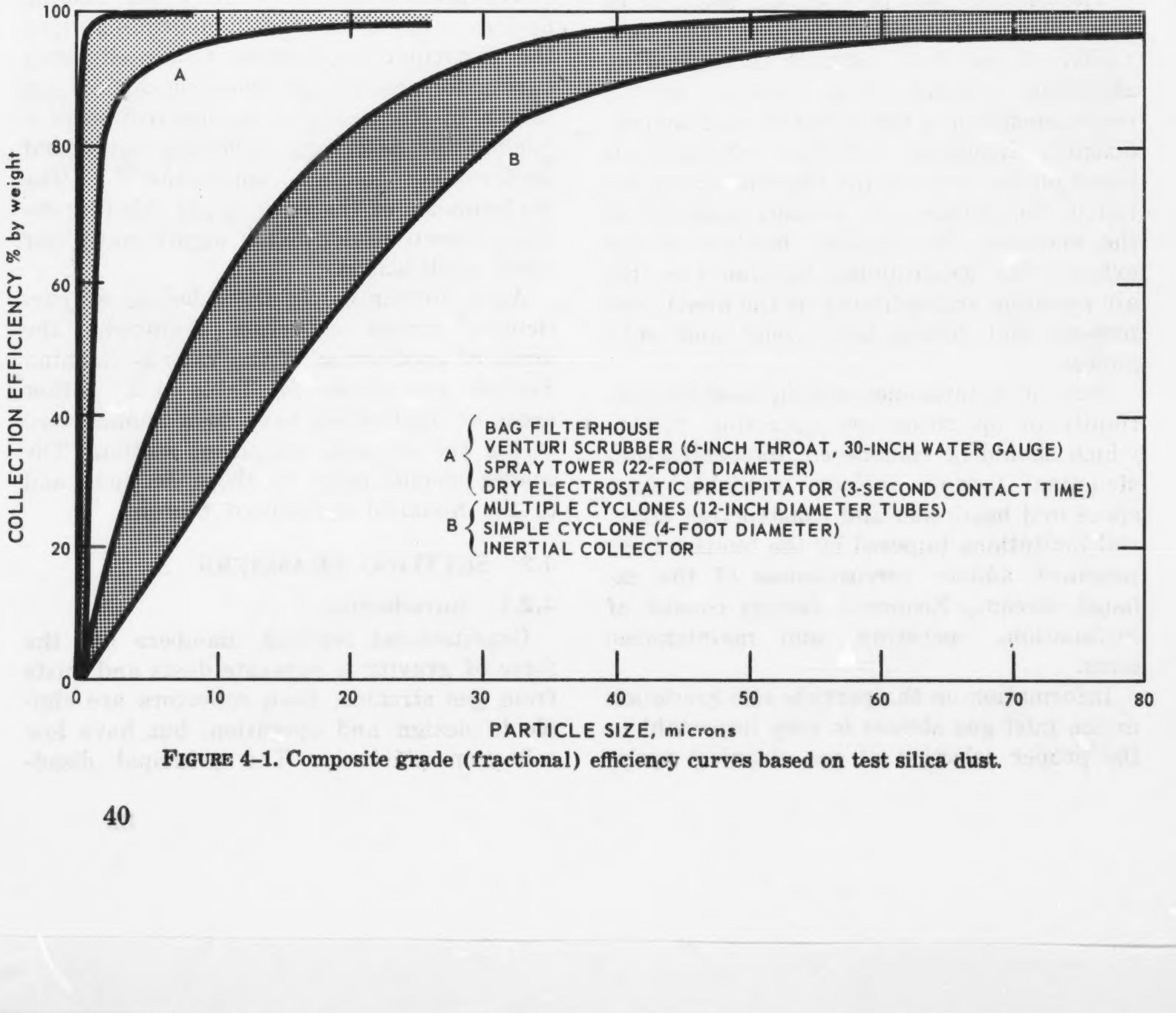


FIGURE 4-1. Composite grade (fractional) efficiency curves based on test silica dust.

Table 4-2 (continued).—USE OF PARTICULATE COLLECTORS BY INDUSTRY[1]

Industrial classification	Process	EP	MC	FF	WS	Other
Steel—Continued.	Taconite	+	0	----	----	----
	Hot scarfing	0	----	----	+	----
Mining and metallurgical	Zinc roaster	0	0	----	----	----
	Zinc smelter	0	----	----	----	----
	Copper roaster	0	0	----	----	----
	Copper reverb	0	----	----	----	----
	Copper converter	0	----	----	----	----
	Lead furnace	----	----	0	0	----
	Aluminum	0	----	----	0	+
	Elemental phos	0	----	----	----	----
	Ilmenite	0	0	----	----	----
	Titanium dioxide	+	----	0	----	----
	Molybdenum	+	----	----	----	----
	Sulfuric acid	0	----	----	0	0
	Phosphoric acid	----	----	----	0	0
	Nitric acid	----	----	----	0	0
	Ore beneficiation	+	+	+	+	+
Miscellaneous	Refinery catalyst	0	0	----	----	----
	Coal drying	----	0	----	----	----
	Coal mill vents	----	+	0	----	----
	Municipal incinerators	+	0	----	0	+
	Carbon black	+	+	+	----	----
	Apartment incinerators	----	----	----	0	----
	Spray drying	----	0	0	+	----
	Machining operation	----	0	0	+	+
	Hot coating	----	----	----	0	0
	Precious metal	0	----	0	----	----
	Feed and flour milling	----	0	0	----	----
	Lumber mills	----	0	----	----	----
	Wood working	----	0	0	----	----

Key:
0 = Most common
+ = Not normally used
EP = Electrostatic Precipitator
MC = Mechanical Collector
FF = Fabric Filter
WS = Wet Scrubber

Other = Packed towers
Mist pads
Slag filter
Centrifugal exhausters
Flame incineration
Settling chamber

vantages are low collection efficiency for small particles and large space requirements.

4.2.2 Discussion of Terms

To assist in understanding the operation of settling chambers, the following terms are discussed:

1. *Terminal Settling Velocity.* A dust particle falling under the influence of gravity attains a constant terminal velocity, which is dependent on the physical properties of the gas through which the particle is falling, as well as the physical properties of the particle, including its size and shape.[7] Terminal settling velocities in air of spheres of different particle densities were calculated and are presented graphically in Figure 4-2.[7]

2. *Pick-Up Velocity.* Gas flow velocities in a settling chamber must be kept below velocities at which reentrainment or "pick-up" occurs,[8, 9] or collection efficiency will be decreased.

3. *Collection Efficiency.* Collection efficiency is represented by the weight fraction of the dust retained in the collector. Theoretical collection efficiency may be represented by the ratio of particle retention time to theoretical settling time and cannot exceed unity.

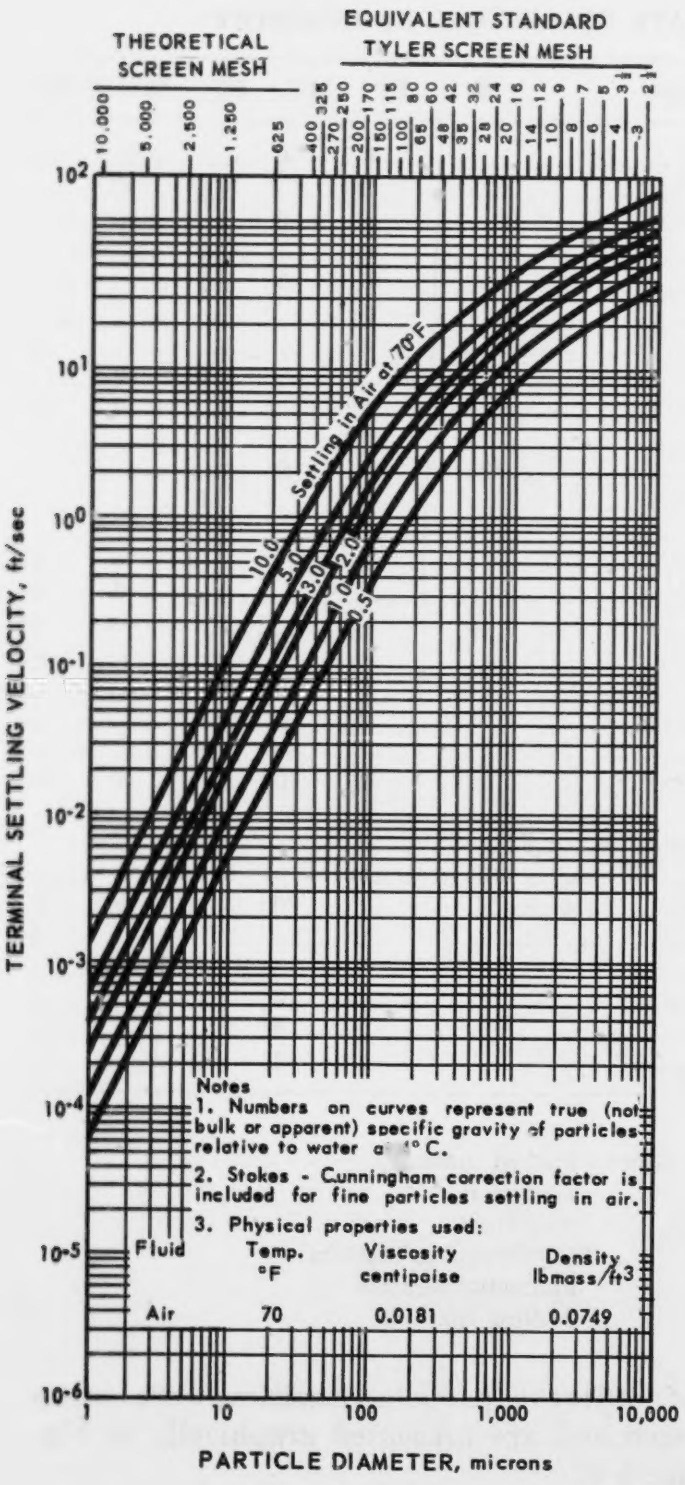


Figure 4-2. Terminal velocities of spherical particles in air. (Adapted from reference 7)

4.2.3 Design Considerations

A gravitational settling chamber consists essentially of a chamber in which the velocity of the carrier gas is decreased so that particles in the gas settle out by gravity. Velocity of a gas is reduced by expanding the ducting into a chamber of suitable dimensions so that a low gas velocity is obtained.

The settling chamber may consist of a simple balloon duct (Figure 4-3), an expansion chamber with dust hopper (Figure 4-4), or dust settling chamber (Figure 4-5). The multiple-tray settling chamber (Figure 4-6) represents one of the first attempts to increase collection efficiency by reducing the vertical settling distance (time) by using multiple shelving. Vertical distance between shelves may be as little as 1 inch. The gas must be uniformly distributed laterally upon entering the chamber; vertical distribution is not critical. Uniform distribution is achieved by the use of gradual transitions, guide vanes, distributor screens, or perforated plates.

Figure 4-3. Balloon duct.

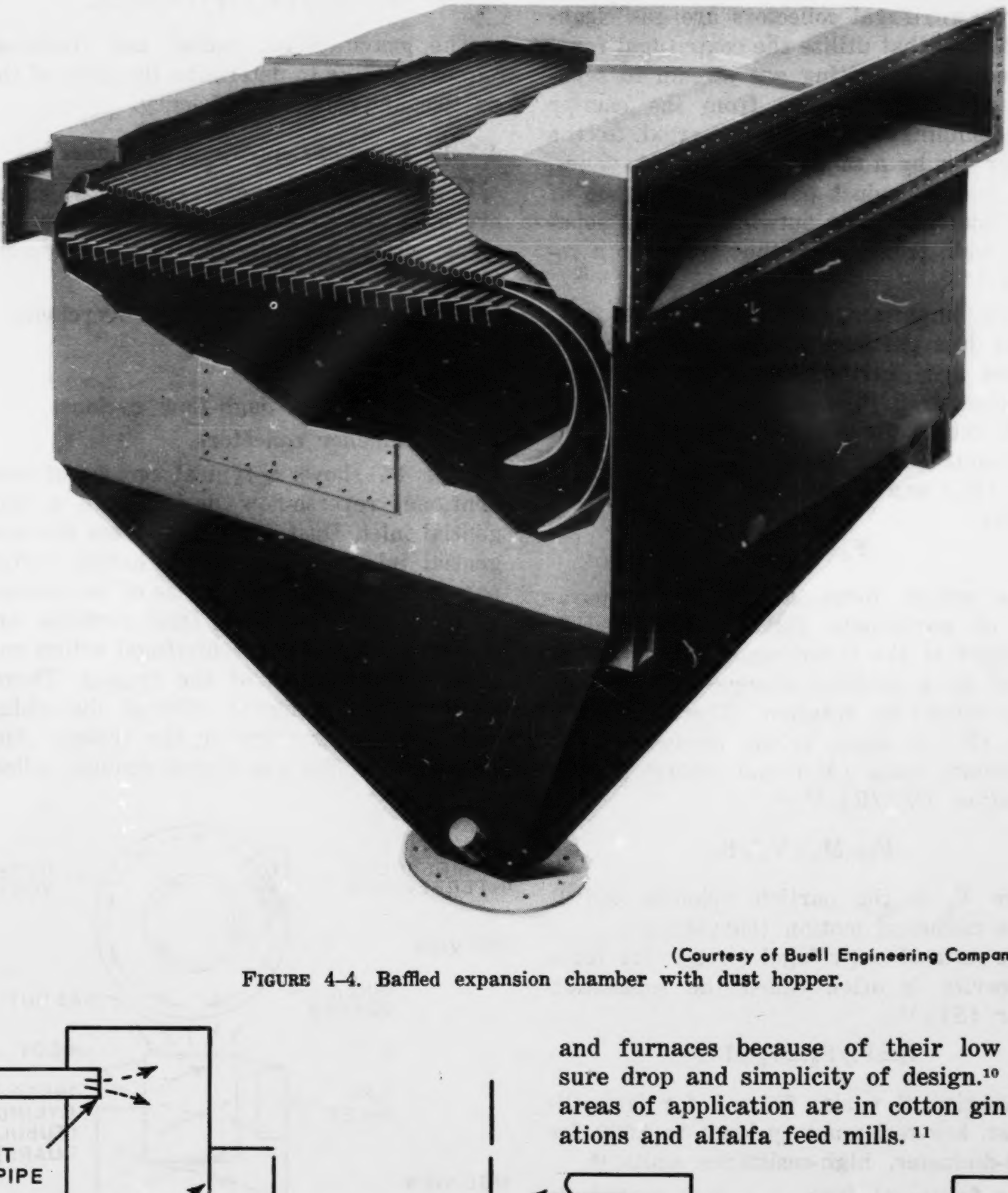
Because the settling rate of dust decreases with increasing turbulence of the gas, the velocity of the gas stream is usually kept as low as possible. For practical purposes, the velocity must not be so great that settled particles are reentrained, or so low that equipment size becomes excessive. Gas velocities are normally from 1 to 10 feet per second.

In practice, gravitational settling velocities used in design must be based on experience or on tests conducted under actual conditions, because terminal settling velocity may be influenced by such factors as agglomeration and electrostatic charge.

4.2.4 Typical Applications

Settling chambers are usually installed as pre-cleaners to remove large particles and agglomerated particles, which can clog small-diameter cyclones and other dust cleaning equipment. Because of space considerations, dust chambers are usually limited to particles larger than 43 microns[7] (325 mesh).

Dust settling chambers are most frequently used on natural draft exhausts from kilns



(Courtesy of Buell Engineering Company, Inc.)

FIGURE 4–4. Baffled expansion chamber with dust hopper.

and furnaces because of their low pressure drop and simplicity of design.[10] Other areas of application are in cotton gin operations and alfalfa feed mills. [11]

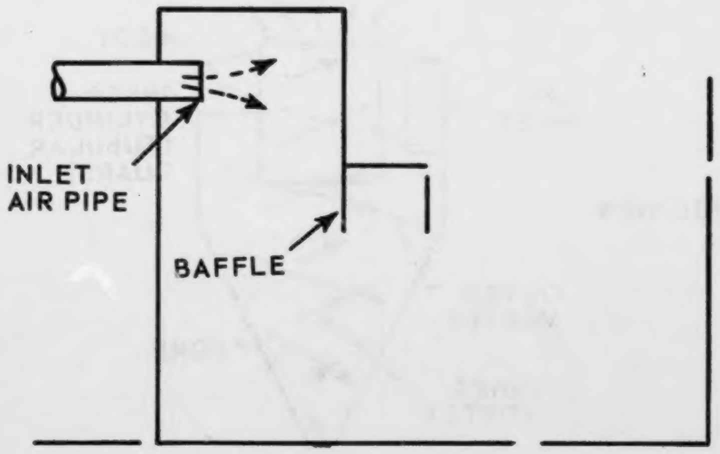


FIGURE 4–5. Dust settling chamber.

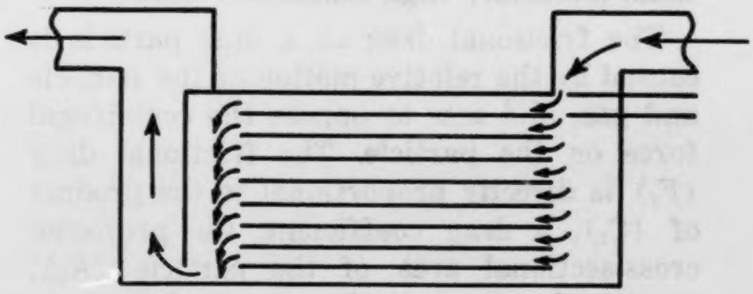


FIGURE 4–6. Multiple-tray dust collector.

4.3 DRY CENTRIFUGAL COLLECTORS

4.3.1 Introduction

Dry centrifugal collectors are gas cleaning devices that utilize the centrifugal force created by a spinning gas stream to separate particulate matter from the carrier gas. Spinning motion is imparted to the carrier gas by a tangential gas inlet, vanes, or a fan. The dust particles, by virtue of their inertia, move outward to the separator wall, from which they travel to a receiver.[12]

Three important forces that act on individual dust particles during the separation process are gravitational, centrifugal, and frictional drag. The force of gravity (F_g), which causes the particulate matter to settle, is equal to the product of the particulate mass (M_p) and acceleration caused by gravity (G).

$$F_g = M_p \times G$$

The major force causing the separation of particulate matter in a cyclone separator is the centrifugal (radial) force caused by a uniform change in linear velocity caused by rotation. The centrifugal force (F_c) is equal to the product of the particulate mass (M_p) and centrifugal acceleration (V_p^2/R).[13, 14]

$$F_c = M_p \times V_p^2/R$$

Where V_p is the particle velocity and R is the radius of motion (curvature).

The ratio of centrifugal force to the force of gravity is often called the separation factor (S):[15]

$$S = F_c/F_g = V_p^2/RG$$

In practice, S varies from 5 for large-diameter, low-resistance cyclones to 2500 for small-diameter, high-resistance units.[16]

The frictional drag on a dust particle is caused by the relative motion of the particle and gas, and acts to oppose the centrifugal force on the particle. The frictional drag (F_f) is directly proportional to the product of (C_f), a drag coefficient, the projected cross-sectional area of the particle (A_p), particle density (p), the square of the particle velocity relative to the gas stream (V_r^2), and an inverse function of the acceleration due to gravity G.

$$F_f = (C_f)(A_p)(p)(V_r^2)/2G$$

The gravitational, radial, and frictional forces combine to determine the path of the particle and collection efficiency.

4.3.2 Types of Centrifugal Collectors

Centrifugal collectors, commonly called cyclones, are made in a wide variety of designs, which generally fall in the following categories:

1. Conventional reverse-flow cyclones.
    a. Tangential inlet.
    b. Axial inlet.
2. Straight-through-flow cyclones.
3. Impeller collectors.

Figure 4-7 shows a typical cyclone of conventional reverse-flow design with a tangential inlet. Dust-laden gas enters the tangential inlet and flows in a helical vortex path that reverses at the base of the cyclone to form an inner cone. Dust particles are forced to the wall by centrifugal action and drop to the bottom of the cyclone. There, dust must be removed without disturbing the vortex of gas flow in the cyclone. Any disruption of the gas stream reduces collec-

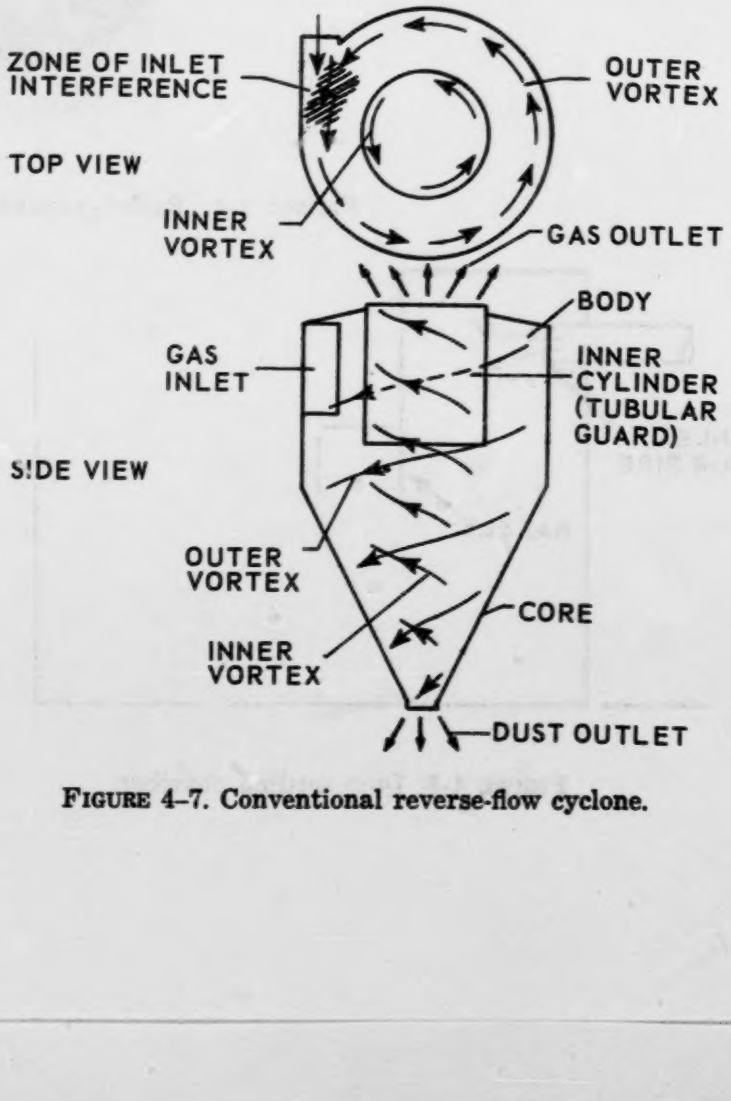


FIGURE 4-7. Conventional reverse-flow cyclone.

tion efficiency and causes particle reentrainment in the gas stream.

Tangential inlet cyclones are categorized as either high-efficiency or high-throughput collectors. The high-efficiency design features a narrow gas inlet which enhances collection because of the shorter radial settling distance and large cross-sectional area between the wall and the dust-laden vortex. These features are typical of many small diameter cyclones. The high-throughput cyclone sacrifices efficiency for volume flow rate and is typical of larger-diameter cyclones.

Although most cyclones use a cone to reverse the gas direction and to deliver the collected dust to a central point for removal, a simple cylinder can be used. Because the cylinder requires a greater axial distance than the cone and thereby adds height and weight to the collector, it is not commonly used.

The axial inlet cyclone is shown in Figure 4-8. Like the tangential inlet cyclone, both the efficiency and pressure drop of axial inlet units are affected by the dimensions of the gas inlet.

In cyclones with straight-through flow (Figure 4-9), particulate matter is collected around the periphery of the base and is bled off to a secondary collector that may be

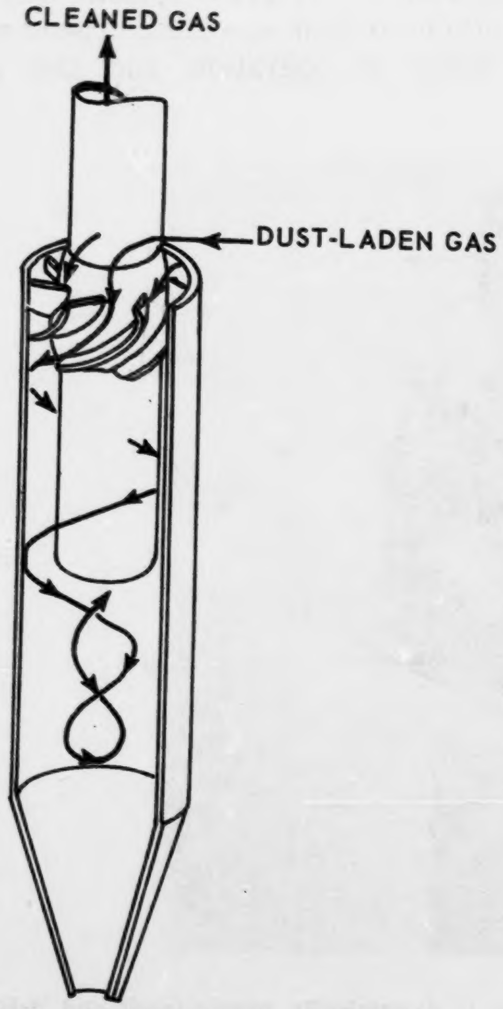


FIGURE 4–8. Axial inlet cyclone.

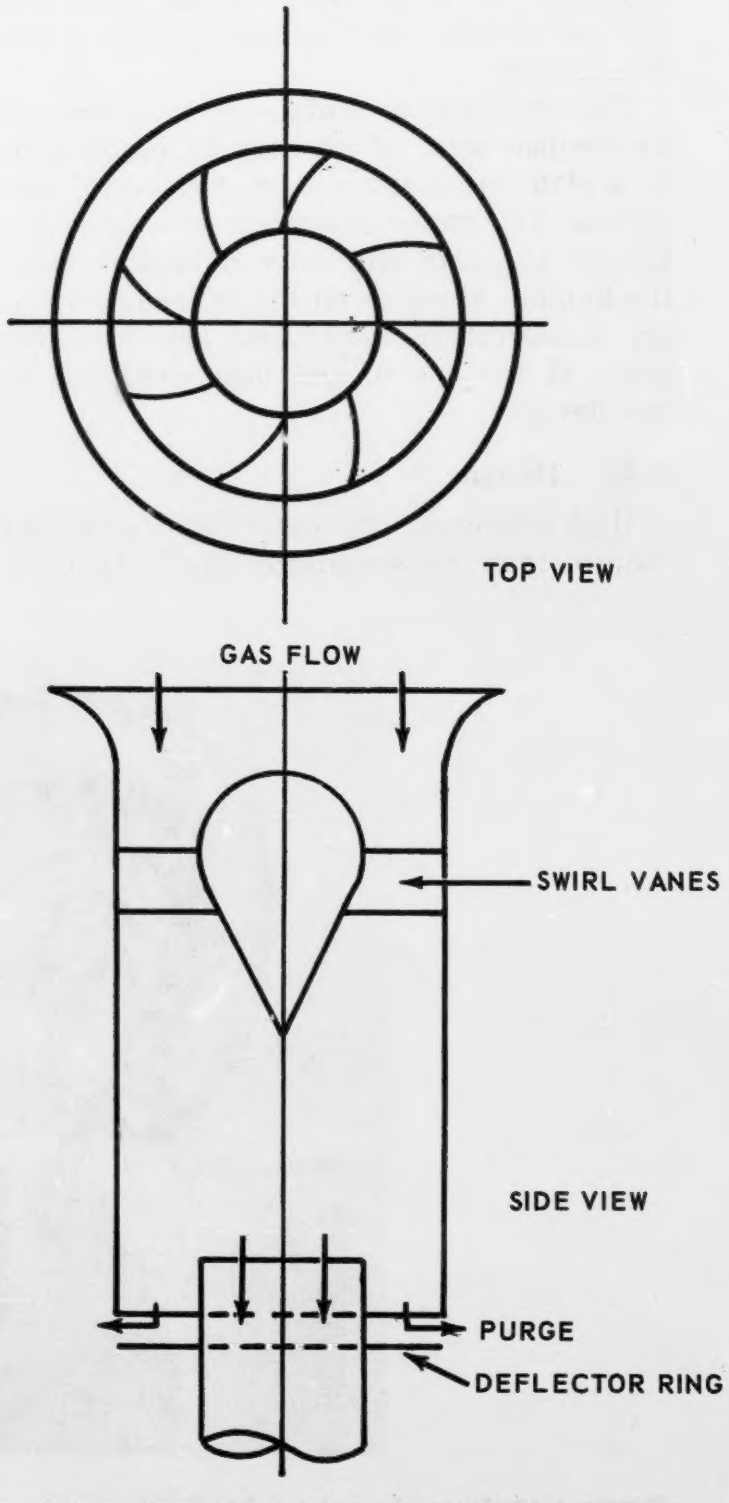


FIGURE 4–9. Straight-through-flow cyclone.
(Courtesy of the American Petroleum Institute)

a cyclone or dust settling chamber. This type of cyclone is used frequently as a fly ash collector and as a precleaner (skimmer) for other types of dust cleaning equipment. The chief advantages of this design are low pressure drop and high gas handling capacity.

In the impeller collector (Figure 4-10), the particulate-laden gas enters the throat of the impeller and passes through a specially shaped fan blade where the dust is thrown into an annular slot leading to the collection hopper.

The principal advantage of this unit is its compactness, which may be of concern in a plant requiring a large number of collectors. The major limitation is a tendency toward plugging and rotor imbalance from the buildup of solids on the rotating impeller. Temperature limitations also exist because of the use of bearings and seals in the device.

4.3.3 Design

High-efficiency, dry centrifugal collectors require that the separation factor be high, and the number of gas revolutions large, and that collected dust be removed to avoid reentrainment. Cyclone dimensional factors, gas characteristics, and dust properties affect dust collection. [15]

Collection efficiency increases with:

1. dust particle size,
2. particle density,
3. inlet gas velocity,
4. cyclone body length,
5. number of gas revolutions,
6. smoothness of cyclone wall.

Collection efficiency decreases with increased:

1. gas viscosity,
2. cyclone diameter,
3. gas outlet duct diameter,
4. gas inlet area.

Cyclone efficiencies are commonly classified as low, medium, and high, corresponding to weight collection efficiency ranges of 50 to 80, 80 to 95, and 95 to 99 percent, respectively. [14] A given cyclone design can fall into more than one class, depending upon the mode of operation and the particle

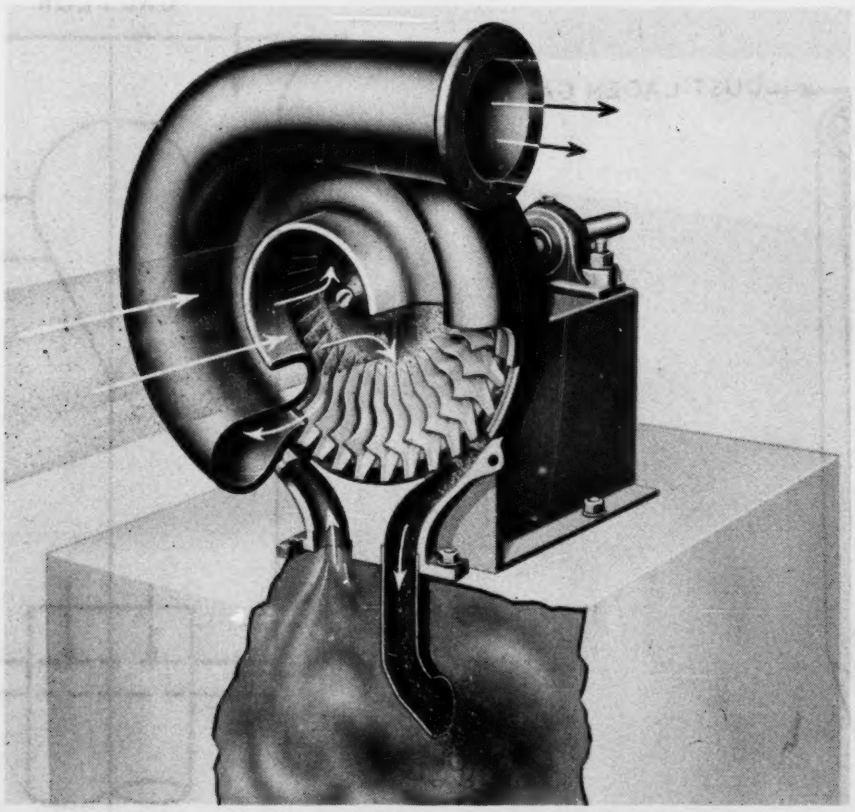


Figure 4-10. Dynamic cyclone showing method by which dust is dynamically precipitated and delivered to the storage hopper.

(Courtesy of American Air Filter Company)

size being collected. For example, a cyclone nominally considered a high-efficiency cyclone could operate in the low collection efficiency range if it were used on a gas stream containing a significant quantity of submicron particles.

In addition to the overall collection efficiency, based on the weight of entrained particulate entering and leaving the collector, performance is also related to cut size. Generally, cut size is defined as the particle diameter collected with 50 percent efficiency on a weight basis.

Particle cut size may be estimated from the Rozin, Rammler, and Intelmann[16] formula:

$$D_{pc}=\sqrt{(9\mu b)/(2\pi N_e V_i(p-g)}$$

where:

D_{pc} =diameter of particle collected with 50 percent efficiency,

μ =gas viscosity,

b =width of cyclone inlet,

N_e =number of effective turns within the cyclone,

V_i =inlet gas velocity,

p =density of the particulate matter, and

g =density of the gas.

Well-designed, large-diameter, conventional cyclones may be expected to provide high collection efficiency for particles from 40 to 50 microns and typically have cut sizes of 8 microns.[15] High-efficiency cyclones having diameters of less than 1 foot operate efficiently on particles of 15 to 20 microns in size and have cut sizes of 3 microns. Typical efficiencies for various particle size ranges are shown in Table 4-3.

Collection efficiency of small-diameter cyclones will be low if much of the suspen[illegible] material is smaller than 5 microns. In sp[illegible]cial cases in which the dust shows a high degree of agglomeration or high dust concentrations are involved (over 100 grains per cubic foot), cyclones will remove dust particles smaller than 5 microns in diameter. The size of the agglomerates is many times larger than the original particles. Efficiencies of as high as 98 percent have been attained on agglomerated dusts having original particle sizes of from 0.1 to 2.0 microns.[17]

Table 4-3.—RELATIONSHIP BETWEEN PARTICLE SIZE RANGE AND CYCLONE EFFICIENCY RANGE[14]

Particle size range, microns	Conventional cyclone efficiency	High cyclone efficiency
Less than 5	—	Low
5 to 20	Low	Medium
15 to 50	Medium	High
Greater than 40	High	High

Factors that commonly cause a reduction in cyclone collection efficiency include infiltration of air at the bottom of the cyclone and the buildup of dust on the cyclone walls. A variety of dust removal methods is available (Figure 4-11). The buildup of dust may be reduced by means of vibrators and flexible rubber cones.[18] Special valves may be used to discharge dust without admitting air.

4.3.3.1 Operating Pressure Drop—The pressure drop across a cyclone depends on a number of variables, but usually ranges from 1 to 8 inches of water. Efficiency increases with increasing inlet velocity,[14] but at a lower rate than that at which the pressure drop increases. For a given cyclone and dust combination, an optimum velocity exists, beyond which turbulence increases more rapidly than separation efficiency, and efficiency decreases.

Pressure drop in a cyclone is due to both frictional and dynamic energy losses, which are interdependent. Frictional losses are determined by cyclone surface roughness, gas velocity, and the physical properties of the gas and aerosol. Dynamic energy loss, on the other hand, is caused by the energy stored in the high-velocity rotating centrifugal gas stream. Part of this energy is lost in the rotating gas leaving the cyclone.

Internal surface roughness can cause an increase in frictional pressure drop, and result in a decrease in overall pressure drop by causing a decrease in rotational gas velocity (dynamic pressure loss) along the outer circumference of the cyclone, with a resultant decrease in collection efficiency.

To lower the pressure drop through a given collector, either a reduction of the rotational velocity (dynamic pressure loss) of

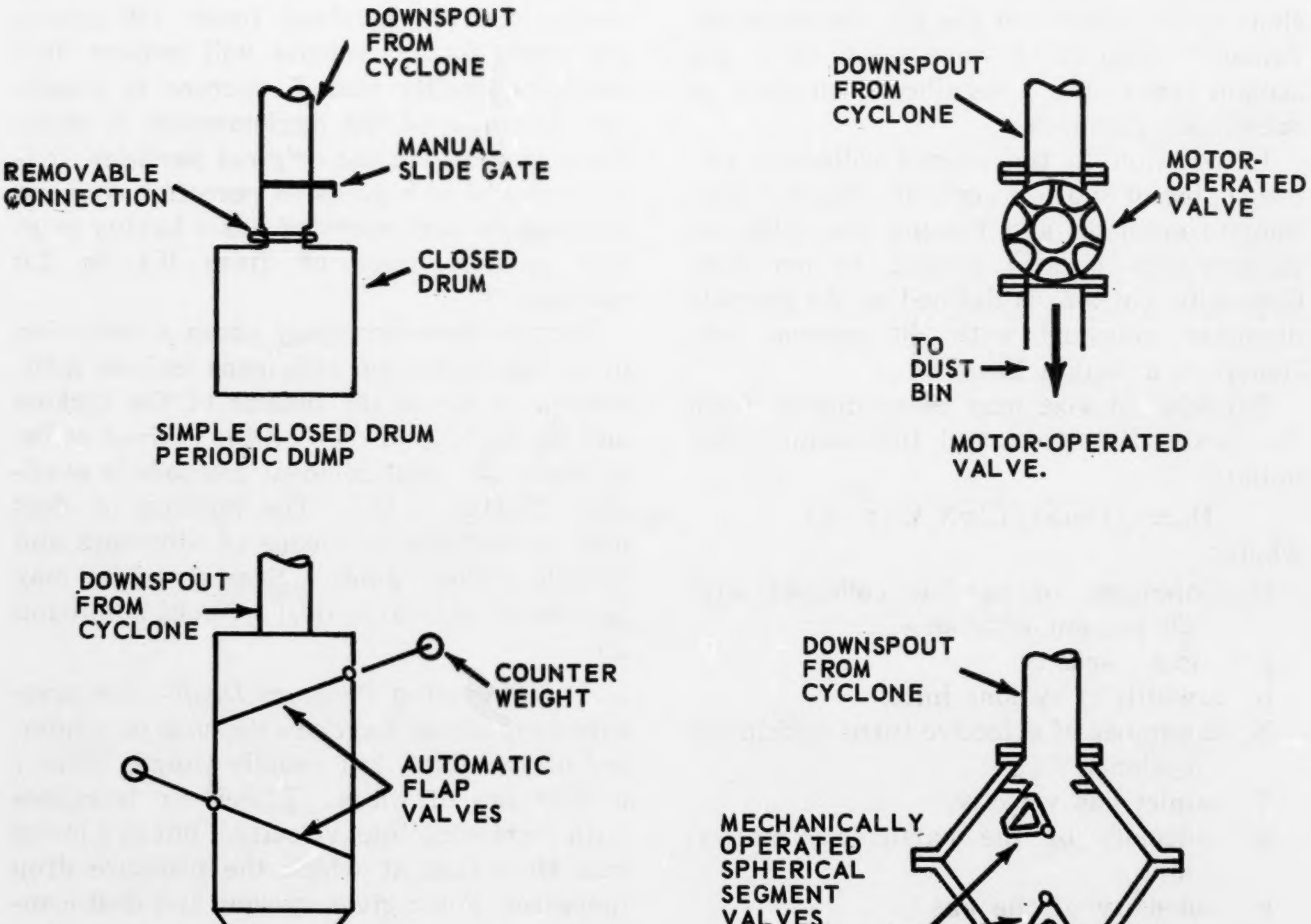

DOWNSPOUT FROM CYCLONE
MANUAL SLIDE GATE
REMOVABLE CONNECTION
CLOSED DRUM
SIMPLE CLOSED DRUM PERIODIC DUMP
DOWNSPOUT FROM CYCLONE
MOTOR-OPERATED VALVE
TO DUST BIN
MOTOR-OPERATED VALVE.
DOWNSPOUT FROM CYCLONE
COUNTER WEIGHT
AUTOMATIC FLAP VALVES
DUST COVER
DUST BIN
AUTOMATIC FLAP VALVES
DOWNSPOUT FROM CYCLONE
MECHANICALLY OPERATED SPHERICAL SEGMENT VALVES OUT OF PHASE
TO DUST BIN
SPHERICAL SEGMENT VALVES FOR HIGH-PRESSURE DIFFERENTIAL
DOWNSPOUT FROM CYCLONE
SCREW FEEDER
SPRING-LOADED CHOKE ON SCREW DISCHARGE
TO DUST BIN
CHOKE DISCHARGE SCREW FEEDER

Figure 4–11. Various types of cyclone dust discharge.

(Courtesy of the American Petroleum Institute)

the clean exit gas or reduction of internal rotational energy (dynamic pressure gain) is used. Pressure recovery from the exit gas may be accomplished by the use of deflection cones, baffles, inverted cones, vanes, or drums and scrolls, but usually at the expense of reduced collection efficiency. Pressure reduction values reported in the literature vary from 10 to 25 percent of the total pressure drop across the cyclone.[14]

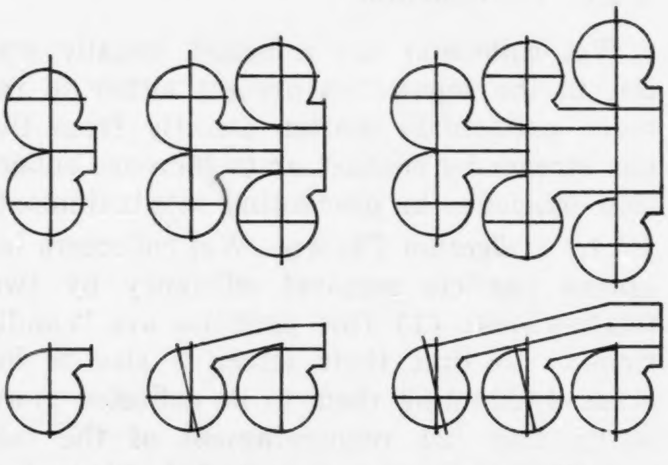


FIGURE 4-12. Cyclones arranged in parallel.
(Courtesy of Buell Engineering Company, Inc.)

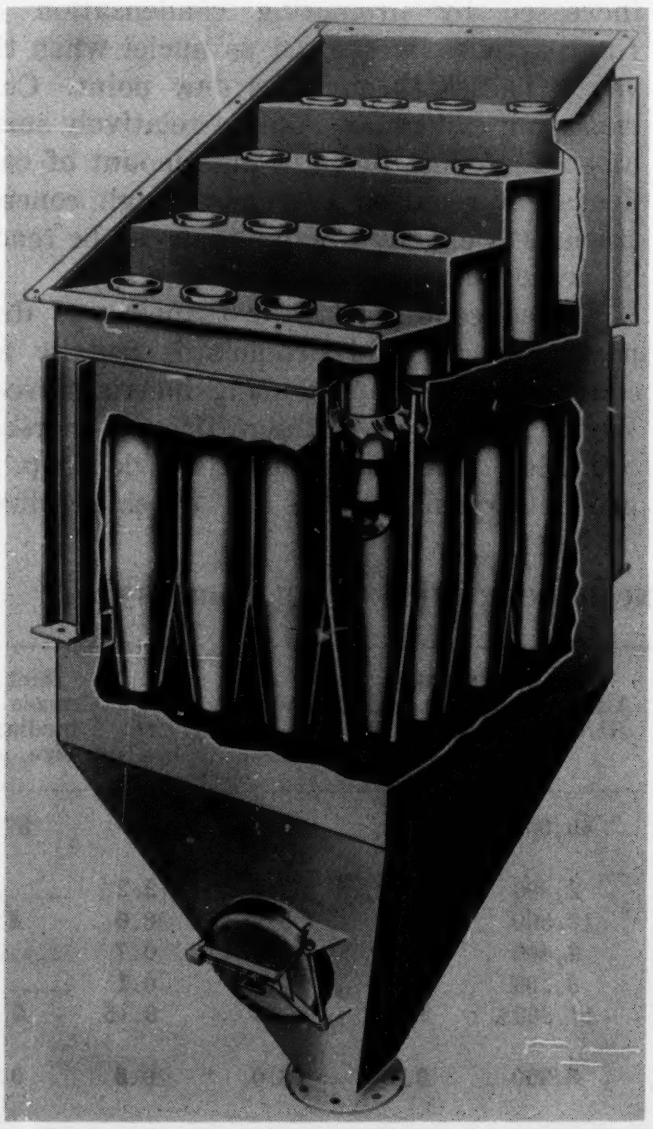


FIGURE 4-13. Cyclones arranged in parallel.
(Courtesy of Western Precipitation Division)

Pressure reduction may also be accomplished by the use of inlet vanes which reduce pressure drop and rotational velocity, and hence collection efficiency. Vanes are used when gas handling capacity is to be increased and/or when normal collection efficiency is so high that loss in efficiency is insignificant.

In the impeller collector, pressure drop and collection efficiency may be increased by restricting the gas outlet. Pressure drop may be as low as ½ inch of water, and pressure gains may even be realized with some units because of the pumping action of the motor-driven impeller.

4.3.3.2 Dust Loading—A cyclone can be designed to handle practically any amount of material that can be moved by gas flow. In general, cyclone efficiency increases with increasing dust load. Since these characteristics are not possessed by other types of collectors with inherently higher efficiencies, cyclones are frequently used as precleaners where dust loadings are too high for the final collector.

Because cyclone efficiencies decrease with decreasing dust load and other types of collectors can operate efficiently at lower dust loadings, cyclones are usually used (1) for dust loadings of more than 10 grains per cubic foot, (2) for coarse or easily flocculated dust loadings of less than 10 grains per cubic foot, or (3) if such factors as high temperature and corrosion exert an overriding influence.

4.3.3.3 Other Design Considerations—Cyclones may be operated in parallel as shown in Figures 4-12 and 4-13. In both configurations, gas distribution becomes critical and collection efficiency is usually lower than the corresponding single-unit efficiency, even in well-designed systems.

Series operation is sometimes justified if the dust is subjected to fragmentation and deflocculation as a result of bouncing within the cyclone, if large particles must be removed to prevent clogging, if abrasion is a problem, or if the primary cyclone loses efficiency. In these cases, the primary cyclone is usually of large-diameter, low-pressure-drop design followed by progressively smaller-diameter cyclones, each with increased efficiency and pressure drop.

Erosion effects increase exponentially with increasing gas velocity. Maximum erosion occurs at an impingement angle of from 20 to 30 degrees, and is approximately twice the erosion occurring at 90 degrees. [19] The effects of erosion may be minimized by the use of special alloys, abrasion-resistant refractories, thicker walls, rubber lining, and by reducing gas velocity.

4.3.4 Typical Applications

Cyclones are frequently used in both primary and secondary gas cleaning and operations. They are used in feed and grain mills, cotton gins, fertilizer plants, petroleum refineries, asphalt mixing plants, metallurgical operations, and chemicals, plastics, and metals manufacture. [20, 21]

Cyclones designed for the collection of mist are sometimes modified by placing an outer skirt on the gas outlet to prevent liquid carryover. Representative performance and applications of centrifugal collectors are listed in Tables 4-4 and 4-5. [22]

4.4 WET COLLECTORS AND MIST ELIMINATORS

4.4.1 Introduction

Wet collectors use a liquid, usually water, in the separation process either to remove particulate matter directly from the gas stream by contact or to increase collection efficiency by preventing reentrainment.

4.4.1.1 Collection Theory—Wet collectors increase particle removal efficiency by two mechanisms: (1) fine particles are "conditioned" so that their effective size is increased, enabling them to be collected more easily and (2) reentrainment of the collected particles is minimized by trapping them in a liquid film and washing them away. [28, 29]

The effective size of the particle may be increased by promoting condensation on fine particles, which act as nuclei when the vapor passes through its dew point. Condensation can remove only a relatively small amount of dust because the amount of condensation required to remove high concentrations is usually greater than can be readily achieved.

Forced conditioning or trapping of dust particles on liquid droplets is usually accomplished by impact using inertial forces. Wetting agents do not significantly increase collection efficiency, but they do help to prevent reentrainment of collected dusts

Table 4-4.—REPRESENTATIVE PERFORMANCE OF CENTRIFUGAL COLLECTORS [20]

Collector type	Process	Material	Airflow, ft³/min	Pressure drop, in. H_2O	Efficiency, wt percent	Inlet load, gr/ft³	Inlet mass median size, μ
Series cyclone	Fluid-catalytic cracking.	Catalyst	40,000	High	99.98	2800	37.0
Cyclone	Abrasive cleaning	Talc	2,300	0.33	93.0	2.2	--------
Cyclone	Drying	Sand and gravel	12,300	1.9	86.9	38.0	8.2 [a]
Cyclone	Grinding	Aluminum	2,400	1.2	89.0	0.7	--------
Cyclone	Planing mill	Wood	3,100	3.7	97.0	0.1	--------
Impeller collectors.	Grinding	Iron scale	11,800	4.7	56.3	0.15	3.2 [b]
Impeller collectors.	Rubber dusting	Zinc stearate	3,300	9.0	88.0	0.6	0.7

[a] Outlet mass median size = 3.2 microns.

[b] Outlet mass median size = 2.5 microns.

that are not easily wetted by water.[30] Solubility of the particle in the droplet is usually not a factor in increasing collection effectiveness.

The principal mechanisms by which particulate matter is brought into contact with liquid droplets [29] are:

1. Interception. Interception occurs when particles are carried by a gas in streamlines around an obstacle at distances of less than the radius of the particle.
2. Gravitational Force. Gravitational force causes a particle, as it passes an obstacle, to fall from the streamline and settle on the surface of the obstacle.
3. Impingement. Impingement occurs when an object, placed in the path of a particle-laden gas stream, causes the gas to flow around the obstacle. Larger particles, however, tend to continue in a straight path because of inertia and may impinge on the obstacle and be collected. (The impingement target efficiency is represented by the ratio of the cross-sectional area of the liquid droplets to the area of the gas stream cleared of particles.)
4. Diffusion. Diffusion results from molecular collisions and, except for submicron particles, plays little part in separation of particles from a gas stream.
5. Electrostatic Forces. Electrostatic forces result when particles and liquid droplets become electrically charged. An electrical charge may be induced by flame ionization or

Table 4-5.—APPLICATIONS OF CENTRIFUGAL COLLECTORS

Operation or process	Air contaminant	Type of air cleaning equipment	Collector efficiency, wt percent	Reference
Crushing, pulverizing, mixing, screening:				
Alfalfa feed mill	Alfalfa dust	Cyclone, settling chamber.	85	23
Barley feed mill	Barley flour dust	Cyclone	85	23
Wheat air cleaner	Chaff	Cyclone	85	23
Drying, baking:				
Catalyst regenerator (petroleum)	Catalyst dust	Cyclone, ESP	95	23
Detergent powder spray drier	Detergent powder	Cyclone	85	23
Orange pulp feed drier	Pulp dust	Cyclone	85	23
Sand drying kiln	Silica dust	Cyclone	78	24
Sand and gravel drying	Silica dust	Inertial collector	50	25
Stone drying kiln	Silica dust	Cyclone	86	24
Mixing fluids:				
Asphalt mixing	Sand and gravel dust	Cyclone	50–86	24
Bituminous concrete mixing	Sand and stone dust	Cyclone, scrubber	95	22
Polishing, buffing, grinding, chipping:				
Grinding (aluminum)	Aluminum dust	Cyclone	89	26
Grinding (iron)	Iron scale and sand	Cyclone	56	25
Grinding (machine shop)	Dust	Impeller collector	91	27
Surface coating rubber dusting	Fluffy zinc stearate	Impeller collector	78–88	26
Surface treatment—physical:				
Abrasive cleaning	Talc dust	Cyclone	93	26
Abrasive stick trimming and shaping.	Silicon carbide and alumina dust.	2 parallel cyclones	51	24
Casting cleaning with metal shot, sandblasting and tumbling.	Metallic and silica dust	Impeller collector	97–99+	27
Foundry tumbling	Dust	Impeller collector	99	27
Truing and shaping abrasive products.	Silicon carbide and alumina dust.	Cyclone	58	24
Woodworking, including plastics rubber, paper board: mill planing.	Wood dust and chips	Cyclone	97	26

friction, or by the presence of charged matter. Electrostatic forces may affect collection efficiency significantly.

6. Thermal Gradients. Thermal gradients are important to the removal of matter from a particle-laden gas stream because particulate matter will move from a hot area to a cold area. The motion is caused by unequal gas molecular collision energy on the surfaces of the hot and cold sides of the particle, and is directly proportional to the temperature gradient.

4.4.1.2 Efficiency—Efficiencies of wet-scrubbing devices are compared on the basis of "contacting power" and the "transfer unit."[31] Contacting power is that portion of useful energy expended in producing contact of the particulate matter with the scrubbing liquid, as well as in producing turbulence and mixing in the scrubber device. The contacting power represents the kinetic energy or pressure head loss across the scrubber, kinetic energy or pressure head drop of the scrubbing liquid, and other forms of energy dissipated in the gas stream, such as sonic energy or energy supplied by a mechanical rotor.

The transfer unit, which is expressed as the numerical value of the natural logarithm of the reciprocal of the fraction of the dust passing through the scrubber, is a measure of the difficulty of separation of the particulate matter.

Dust collection efficiency is believed by some investigators to be directly related to contacting power and the properties of the aerosol and to have little relationship to scrubber design and geometry.[31] Others believe design details are important in the effort to achieve maximum collection efficiency for a given pressure drop.

Gas cleaning equipment is usually selected on the basis of required collection efficiency.[32] There are other factors such as gas temperature and humidity and dust stickiness and abrasiveness that may exert an overriding influence on the final choice. In the following discussion principal design features of the various groups of wet collectors are reviewed from the point of view of general suitability under different operating conditions.

In general, particle size distribution and operating conditions will determine collection efficiencies, which, in turn, will determine power requirements for a given unit.

4.4.2 Equipment Description and Design

Collection efficiencies, operating pressure drop, water requirements, and other operating characteristics reported herein were obtained from manufacturers' equipment bulletins and other literature sources.

4.4.2.1 Spray Chamber—The simplest type of wet scrubber is a round or rectangular spray chamber into which water is introduced by means of spray nozzles.[33]

When spray chambers are used to remove coarse particles from hot gases, they perform the additional functions of gas cooling and humidification. Spray chambers also effect preliminary conditioning of the particulate matter by causing condensation of moisture on particles, thus increasing collection efficiency by increasing the size of the particles.

The principal three configurations in a spray chamber are cocurrent flow, countercurrent flow, and cross flow.[34]

In cocurrent flow, both the spray droplets and the gas containing particulate matter flow through the spray chamber in the same direction. The relative velocity of the water droplet and gas stream causing effective collision and capture of the particulate matter is at a minimum, as is collection efficiency. Part of the kinetic energy of the spray droplets is expended in inducing gas circulation and motion within the scrubber.

Countercurrent flow occurs when the liquid and gas flow in opposite directions, as in a spray tower in which the liquid is introduced in the top of the tower and falls against the rising gas stream. The relative velocity of the liquid droplets and particulate matter in the gas stream is at a maximum, as is collection efficiency.

In cross flow operation, the liquid is introduced at right angles to the direction of gas flow and falls across the gas stream.

The relative velocity of the particulate and liquid droplet and the impaction efficiency lie between the cross flow and countercurrent flow methods of operation.

For a given spray chamber design, mixed flow usually occurs because of turbulence, liquid droplet inertia, and gravitational force. Liquid droplets travel in the direction of the liquid stream until inertial forces are overcome by air resistance. Large droplets settle under the influence of gravity while smaller droplets may be swept along with the gas stream.

Liquid droplets and particulate matter may be separated from the gas stream by gravitational settling, impaction on baffles, filtration through shallow packed beds, or by cyclonic action.

Spray chambers are used in exhaust systems for light dust cleaning, electroplating fume control, and preconditioning dust from acid phosphate fertilizers,[34] as well as for providing a final cleanup of exhaust gases from the recovery furnaces in the kraft pulp manufacturing process.[35]

Figure 4-14 shows a spray system installed in the base of a stack.[33] When the system is properly adjusted and operated, 60 to 80 percent of the solids entering the spray zone may be collected during soot-blowing operations.[36] Approximately ½ gallon of liquid per minute per square foot of stack cross sectional area is required.

The smokestack soot wet-out surface area may also be increased by packing the smokestack (Figure 4-14). The pieces of packing are usually stacked and of large diameter to minimize pressure drop and fouling of the bed. Extra draft fan capacity must be available to make up for the decrease in draft

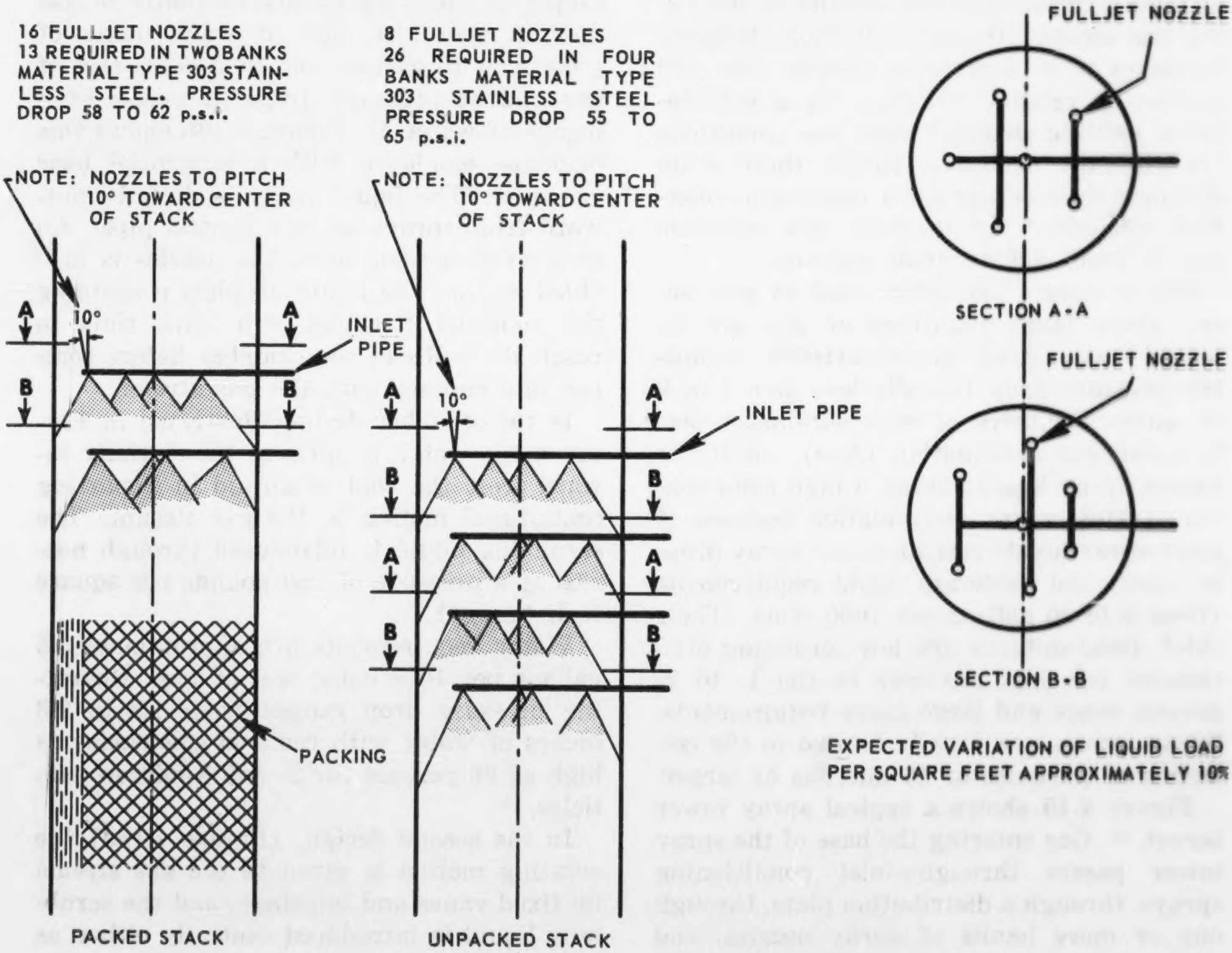

16 FULLJET NOZZLES
13 REQUIRED IN TWO BANKS MATERIAL TYPE 303 STAINLESS STEEL. PRESSURE DROP 58 TO 62 p.s.i.
8 FULLJET NOZZLES
26 REQUIRED IN FOUR BANKS MATERIAL TYPE 303 STAINLESS STEEL PRESSURE DROP 55 TO 65 p.s.i.
NOTE: NOZZLES TO PITCH 10° TOWARD CENTER OF STACK
NOTE: NOZZLES TO PITCH 10° TOWARD CENTER OF STACK
A
B
10°
INLET PIPE
INLET PIPE
PACKING
PACKED STACK
UNPACKED STACK
FULLJET NOZZLE
SECTION A-A
FULLJET NOZZLE
SECTION B-B
EXPECTED VARIATION OF LIQUID LOAD PER SQUARE FEET APPROXIMATELY 10%

FIGURE 4-14. Arrangement of nozzles in smoke stack spray system.

(Courtesy of Spraying Systems Company)

caused by lower flue gas temperature and by packing. The bed must be cleaned periodically by flooding with water.

4.4.2.2 Gravity Spray Towers—One of the simplest types of wet scrubbers is the gravity spray tower. Liquid droplets, produced by either spray nozzles or atomizers, fall downward through a countercurrent rising gas stream containing dust particles. To avoid spray droplet entrainment and carryover, the terminal settling velocity of the spray droplets must be greater than the velocity of the rising gas stream. In practice, the vertical gas velocity usually ranges from 2 to 5 feet per second. For higher velocities, a mist eliminator must be used in the top of the tower.

Collection impingement target efficiency in a gravity spray tower is influenced by the difference between the free-falling velocity of these particles and the velocity of the rising gas stream. Droplet collection efficiency increases with decreasing droplet size and increasing relative velocity. In a gravitational settling chamber these two conditions are mutually exclusive. Hence, there is an optimum droplet size for a maximum collection efficiency.[37] In practice, this optimum size is from 500 to 1000 microns.

Spray towers are often used as precoolers where large quantities of gas are involved. Operating characteristics include low pressure drop (usually less than 1 inch of water, exclusive of mist eliminator section and gas distribution plate), ability to handle spray liquid having a high solid content (using water recirculation because of large spray nozzle clearance and spray droplet size), and moderate liquid requirements (from 5 to 20 gallons per 1000 cfm). Their chief disadvantages are low scrubbing efficiencies for dust particles in the 1- to 2-micron range and large space requirements. Spray towers are usually limited to the collection of particles of 10 microns or larger.

Figure 4-15 shows a typical spray tower layout.[33] Gas entering the base of the spray tower passes through inlet conditioning sprays, through a distribution plate, through one or more banks of spray nozzles, and through a mist eliminator section. The mist eliminator is usually necessary in a tower operating at gas velocities of over 6 feet per second.

The base gas distributor plate may consist of a perforated plate with uniform hole distribution or a support plate covered with from 6 to 12 inches of tower packing.

4.4.2.3 Centrifugal Spray Scrubbers—The efficiency of collection of particles smaller than those recovered in a gravitational spray tower can be improved by increasing the relative velocity of the droplets and gas stream. This may be achieved by using the centrifugal force of a spinning gas stream.

Centrifugal spray scrubbers are of two types. In the first type the spinning motion is imparted to the gas stream by a tangential entry such as shown in Figure 4-16a. The principal benefit is derived from the wetted walls, which prevent reentrainment of separated material. Best collection is obtained by spraying countercurrently to gas flow in the inlet duct at water rates of from 5 to 15 gallons per 1000 cubic feet of gas and at pressure drops in excess of 3 inches of water.[37] Figure 4-16b shows this principle employed with a tangential base gas inlet. The liquid spray is directed outward from sprays set in a central pipe. An unsprayed section above the nozzles is provided so that the liquid droplets containing the collected particles will have time to reach the walls of the chamber before coming into contact with the gas stream.

In the scrubber design illustrated in Figure 4-16c water is sprayed tangentially inward from the wall as an aid in imparting centrifugal motion to the gas stream. The scrubbing liquid is introduced through nozzles at a pressure of 400 pounds per square inch (gauge).

Water requirements are approximately 5 gallons per 1000 cubic feet of gas. Operating pressure drop ranges from 1.3 to 2.3 inches of water with removal efficiencies as high as 96 percent for 2- and 3-micron particles.[38]

In the second design, (Figure 4-16d) the rotating motion is given to the gas stream by fixed vanes and impellers, and the scrubbing liquid is introduced centrally either as a spray or liquid stream.[39]

This type of scrubber is used as a final

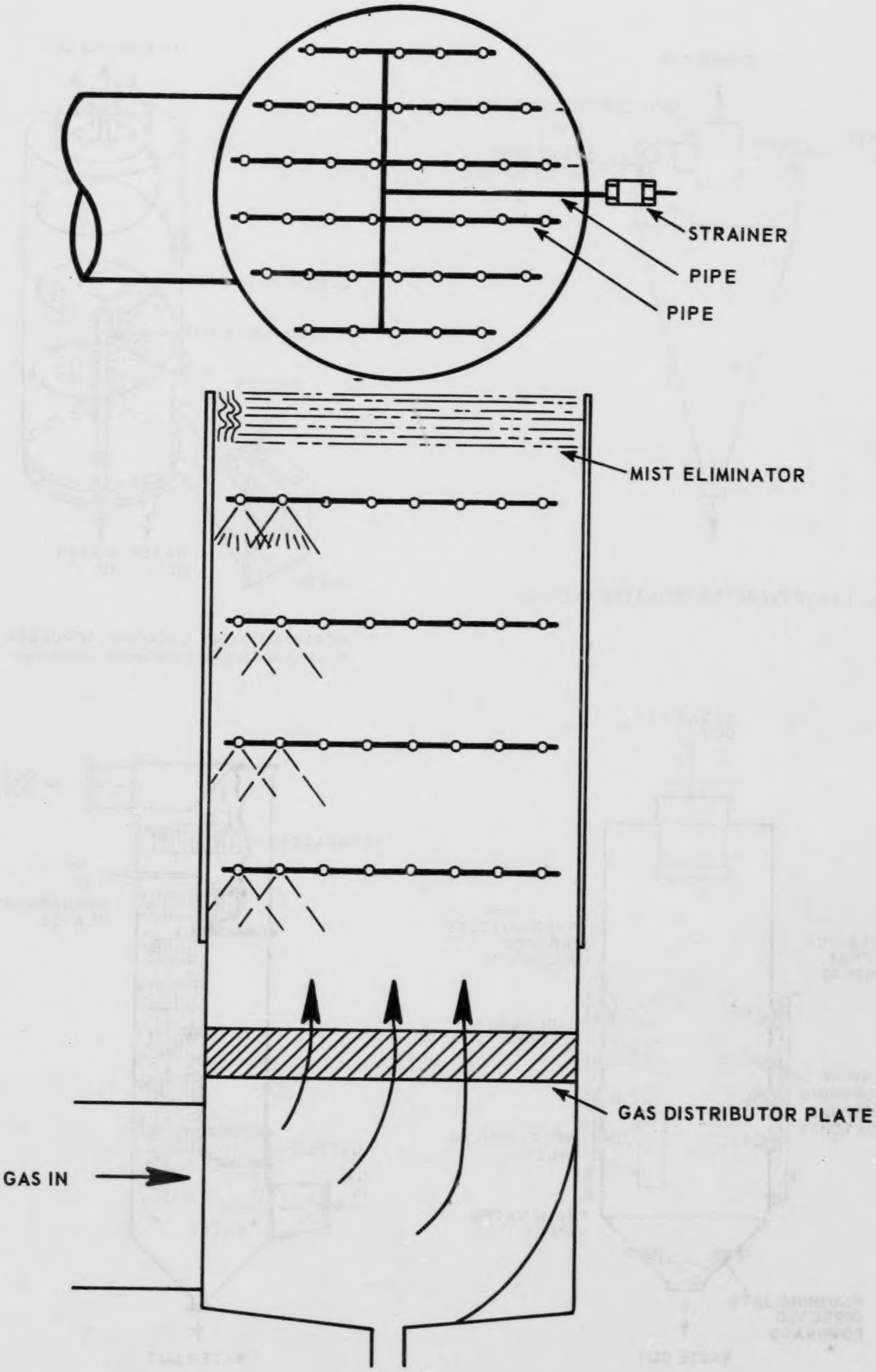
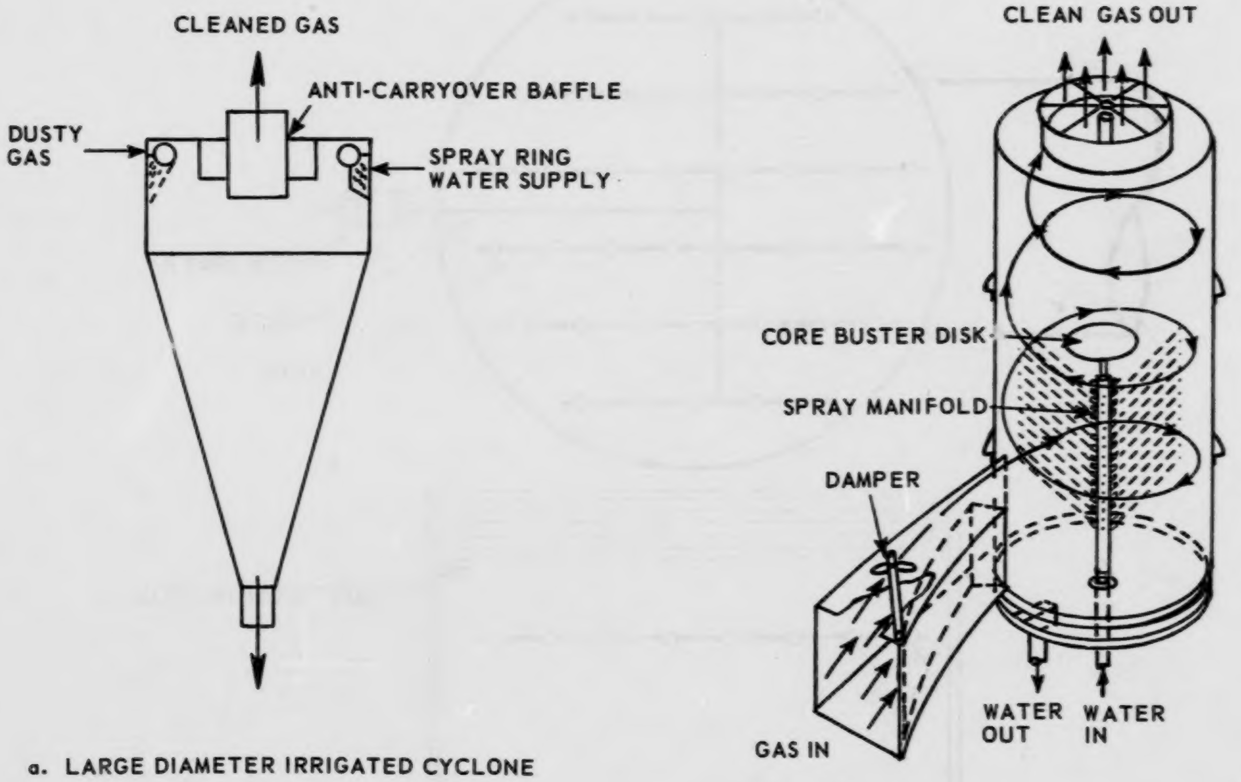

STRAINER
PIPE
PIPE
MIST ELIMINATOR
GAS DISTRIBUTOR PLATE
GAS IN

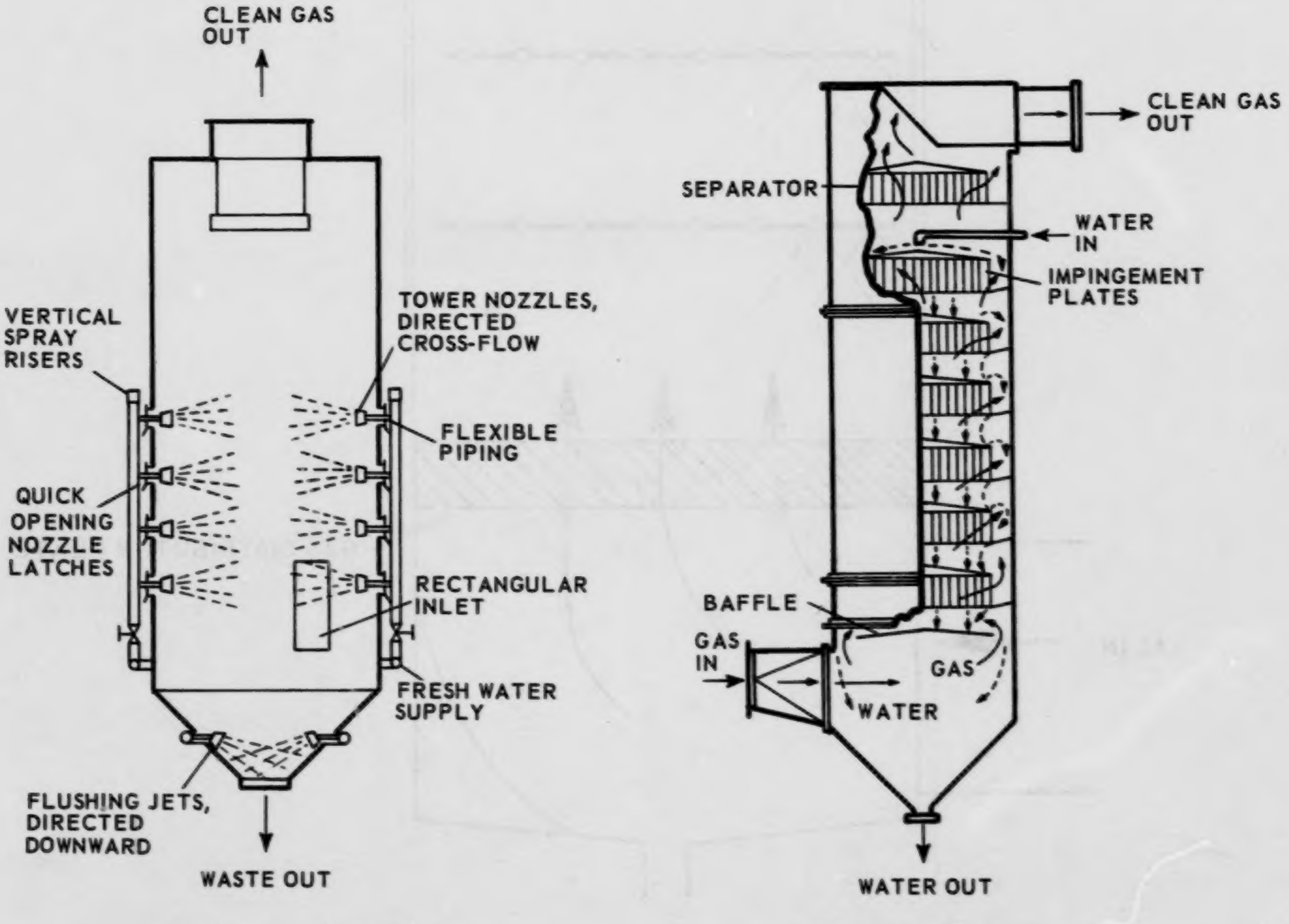
FIGURE 4–15. Typical layout for spray tower.

(Courtesy of Spraying Systems Company)


CLEANED GAS
ANTI-CARRYOVER BAFFLE
DUSTY GAS
SPRAY RING WATER SUPPLY
CLEAN GAS OUT
CORE BUSTER DISK
SPRAY MANIFOLD
DAMPER
WATER OUT
WATER IN
GAS IN

a. LARGE DIAMETER IRRIGATED CYCLONE

b. PEASE ANTHONY CYCLONIC SCRUBBER
(Courtesy of Chemical Construction Corporation)


CLEAN GAS OUT
VERTICAL SPRAY RISERS
TOWER NOZZLES, DIRECTED CROSS-FLOW
FLEXIBLE PIPING
QUICK OPENING NOZZLE LATCHES
RECTANGULAR INLET
FRESH WATER SUPPLY
FLUSHING JETS, DIRECTED DOWNWARD
WASTE OUT
CLEAN GAS OUT
SEPARATOR
WATER IN
IMPINGEMENT PLATES
BAFFLE
GAS IN
GAS
WATER
WATER OUT

c. CYCLONIC SPRAY SCRUBBER.
(Courtesy of Buffalo Forge Company)

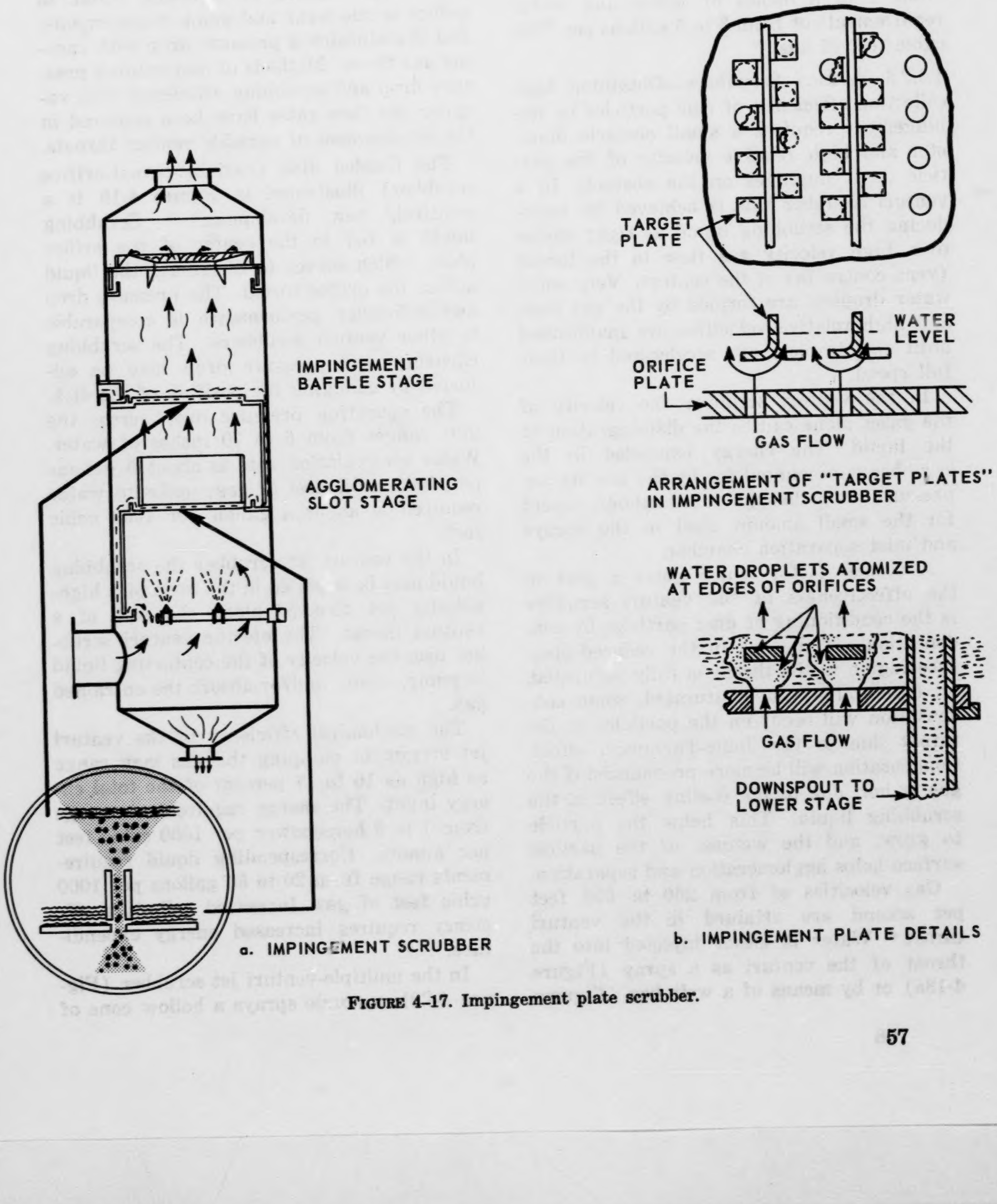
d. MULTI-WASH SCRUBBER.
(Courtesy of Claude B. Schneible Company)

FIGURE 4–16. Centrifugal spray scrubbers.

cleanup after spray dryers, calciners, coolers, crushers, classifiers, and cupolas.

4.4.2.4 Impingement Plate Scrubbers—Impingement plate scrubbers, shown in Figure 4-17a, consist of a tower equipped with one or more impingement stages, mist removal baffles, an dspray chambers.[37] The impingement stage (Figure 4-17b) consists of a perforated plate that has from 600 to 3000 holes per square foot and a set of impingement baffles so arranged that a baffle is located directly above each hole. The perforated plate is equipped with a weir to control the level of scrubbing liquid on the plate. The liquid flows over the plate and through a downcomer to either a sump or the lower stage.

The dust-laden gas enters the lower section of the scrubber and passes up through


IMPINGEMENT BAFFLE STAGE
AGGLOMERATING SLOT STAGE
TARGET PLATE
WATER LEVEL
ORIFICE PLATE
GAS FLOW
ARRANGEMENT OF "TARGET PLATES" IN IMPINGEMENT SCRUBBER
WATER DROPLETS ATOMIZED AT EDGES OF ORIFICES
GAS FLOW
DOWNSPOUT TO LOWER STAGE

a. IMPINGEMENT SCRUBBER

b. IMPINGEMENT PLATE DETAILS

FIGURE 4-17. Impingement plate scrubber.

a spray zone created by a group of low-pressure sprays. As the dust-laden gas passes through the impingement stage, the high gas and particle velocity (from 75 to 100 feet per second) effectively atomizes the liquid at the edges of the perforations. The spray droplets, about 10 microns in size, enhance collection of fine dust.

Overall efficiency for a single plate may range from 90 to 98 percent for 1-micron particles or larger, with pressure drops of from 1 to 8 inches of water and water requirements of from 3 to 5 gallons per 1000 cubic feet of gas.[37]

4.4.2.5 Venturi Scrubbers—Obtaining high collection efficiency of fine particles by impingement requires a small obstacle diameter and high relative velocity of the particle as it impinges on the obstacle. In a venturi scrubber this is achieved by introducing the scrubbing liquid at right angles to a high velocity gas flow in the throat (vena contracta) of the venturi. Very small water droplets are formed by the gas flow, and high relative velocities are maintained until the droplets are accelerated to their full speed.

In the venturi scrubber the velocity of the gases alone causes the disintegration of the liquid. The energy expended in the scrubber is accounted for by the gas stream pressure drop through the scrubber, except for the small amount used in the sprays and mist separation chamber.

A second factor which plays a part in the effectiveness of the venturi scrubber is the conditioning of dust particles by condensation. If the gas in the reduced-pressure region in the throat is fully saturated, or (preferably) supersaturated, some condensation will occur on the particles in the throat due to the Joule-Thompson effect. Condensation will be more pronounced if the gas is hot, due to the cooling effect of the scrubbing liquid. This helps the particle to grow, and the wetness of the particle surface helps agglomeration and separation.

Gas velocities of from 200 to 600 feet per second are attained in the venturi throat.[40] Water is either injected into the throat of the venturi as a spray (Figure 4-18a) or by means of a weir box (Figures 4-18b and 4-18c) in quantities of from 5 to 7 gallons per 1000 cubic feet of gas.

Figures 4-18b and 4-18c show a scrubber that uses an overflow weir on the walls upstream of the venturi. This method of water injection has the advantage of allowing the scrubbing water to be recirculated to much greater extent than is possible with systems using small jets.

Recent developments have taken the form of finding methods of injecting water to reduce nozzle wear and pump requirements, and in maintaining pressure drop with varying gas flows. Methods of maintaining pressure drop and scrubbing efficiency with varying gas flow rates have been centered in the development of variable venturi throats.

The flooded disk (variable-throat-orifice scrubber) illustrated in Figure 4-19 is a relatively new development.[41] Scrubbing liquid is fed to the center of the orifice plate, which serves to distribute the liquid across the orifice throat. The pressure drop and efficiency performance is comparable to other venturi scrubbers. The scrubbing efficiency and pressure drop may be adjusted by changing the position of the disk.

The operating pressure drop across the unit ranges from 6 to 70 inches of water. Water recirculation rate is about 5 gallons per 1000 cubic feet of gas; make-up water required is about a gallon per 1000 cubic feet.

In the venturi jet scrubber the scrubbing liquid may be supplied in the form of a high-velocity jet directed along the axis of a venturi throat. The ejector venturi scrubber uses the velocity of the contacting liquid to pump, scrub, and/or absorb the entrained gas.

The mechanical efficiency of the venturi jet stream in pumping the gas may range as high as 16 to 17 percent of the total energy input. The energy requirements range from 1 to 5 horsepower per 1000 cubic feet per minute. Correspending liquid requirements range from 20 to 50 gallons per 1000 cubic feet of gas. Increased collection efficiency requires increased energy expenditure.[42, 43]

In the multiple-venturi jet scrubber (Figure 4-20), a nozzle sprays a hollow cone of water into the belled venturi entrance so that the spray strikes the throat wall and rebounds in the form of a fine spray at right angles to the gas stream. The water passes through the gas stream twice before passing through the venturi diffuser section. Features of the design are low water usage and low pressure drop.[44]

The vertical venturi differs from the conventional venturi scrubber in that the gas flow is directed upward to produce a turbulent mixing action of the gas stream and sus-

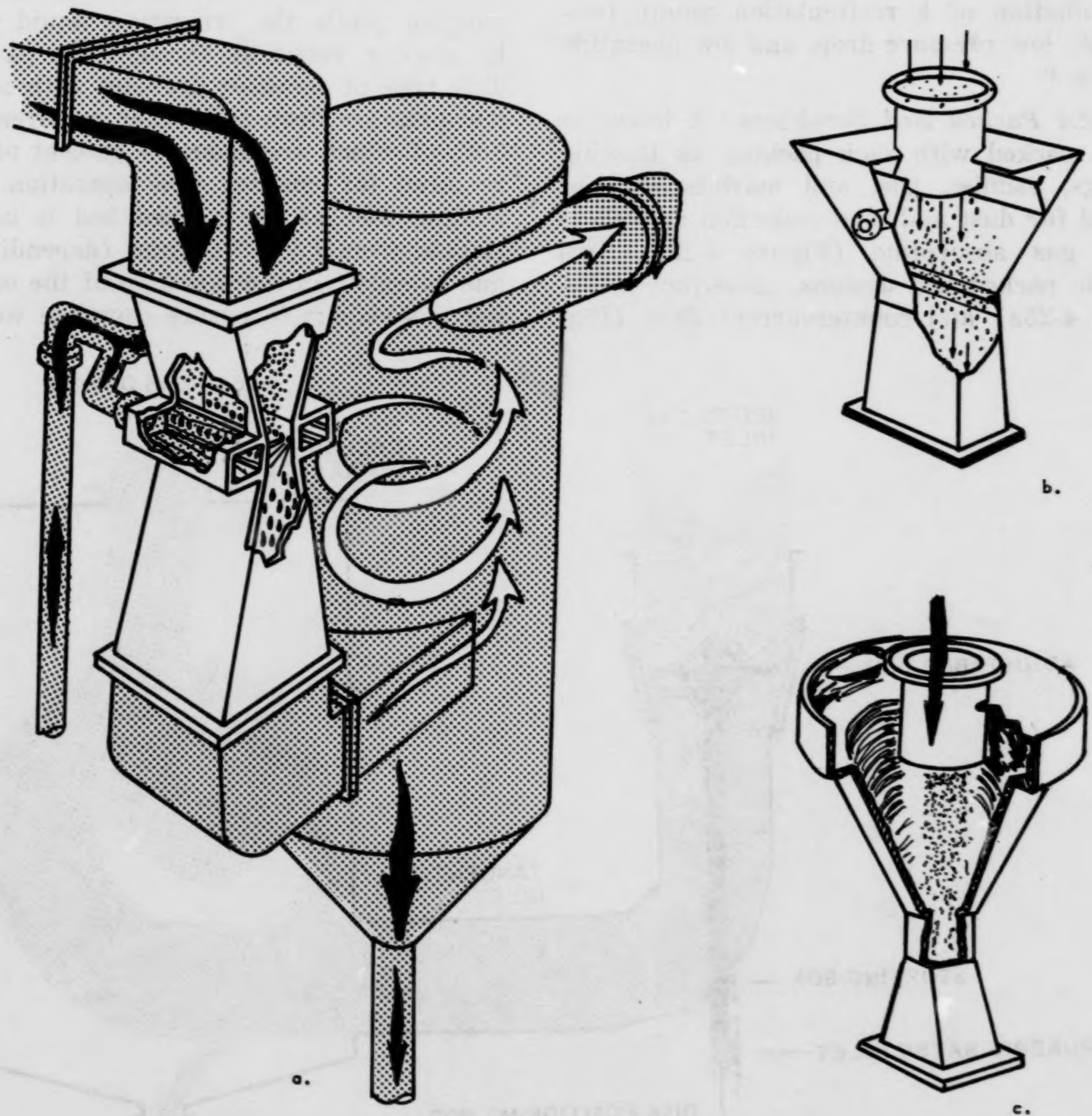


Figure 4–18. Venturi scrubber may feed liquid through jets (a), over a weir (b), or swirl them on a shelf (c).

(Courtesy of UOP Air Correction Division)

pending scrubbing liquid in the diffuser section of the venturi (Figure 4-21). Liquid recirculation occurs both internally by eddy mixing action in the diffuser and externally by return of the scrubbing liquid, after partial solids separation, to the venturi throat. The carryover slurry, when separated by the centrifugal action of the gas stream caused by the stationary impeller, returns by gravity to the solids concentrator. The principal advantages of this design are high solids content of slurry, low water usage (1 to 3 gallons per 1000 cubic feet of gas), elimination of a recirculation pump, relatively low pressure drop, and low operating costs. [45]

4.4.2.6 Packed Bed Scrubbers—A tower or box packed with such packing as Raschig rings, saddles, tile, and marbles may be used for dust and mist collection as well as for gas absorption (Figure 4-22). Two basic packed bed designs, cross-flow (Figure 4-23a) and countercurrent flow (Figure 4-23b) exist. The packed bed may be held in place (fixed), free to move (fluid), or covered with water (flooded). The irrigating liquid serves to wet, dissolve, and/or wash the entrained particulate matter from the bed. Dry beds may be used for the elimination of mists. In general, smaller-diameter tower packing gives a higher particle target efficiency than larger-sized packing for a given gas velocity.

The cross flow, fixed bed, packed scrubber (Figure 4-23a) operates with the gas stream moving horizontally through the packing while the irrigating liquid flows by gravity vertically through the packing. This type of scrubber operates with a very low pressure drop and water requirements, both of which are about 40 percent of that required for counter flow operation. The leading face of the packed bed is usually slanted from 7 to 10 degrees (depending on gas velocity) in the direction of the oncoming gas stream to ensure complete wetting

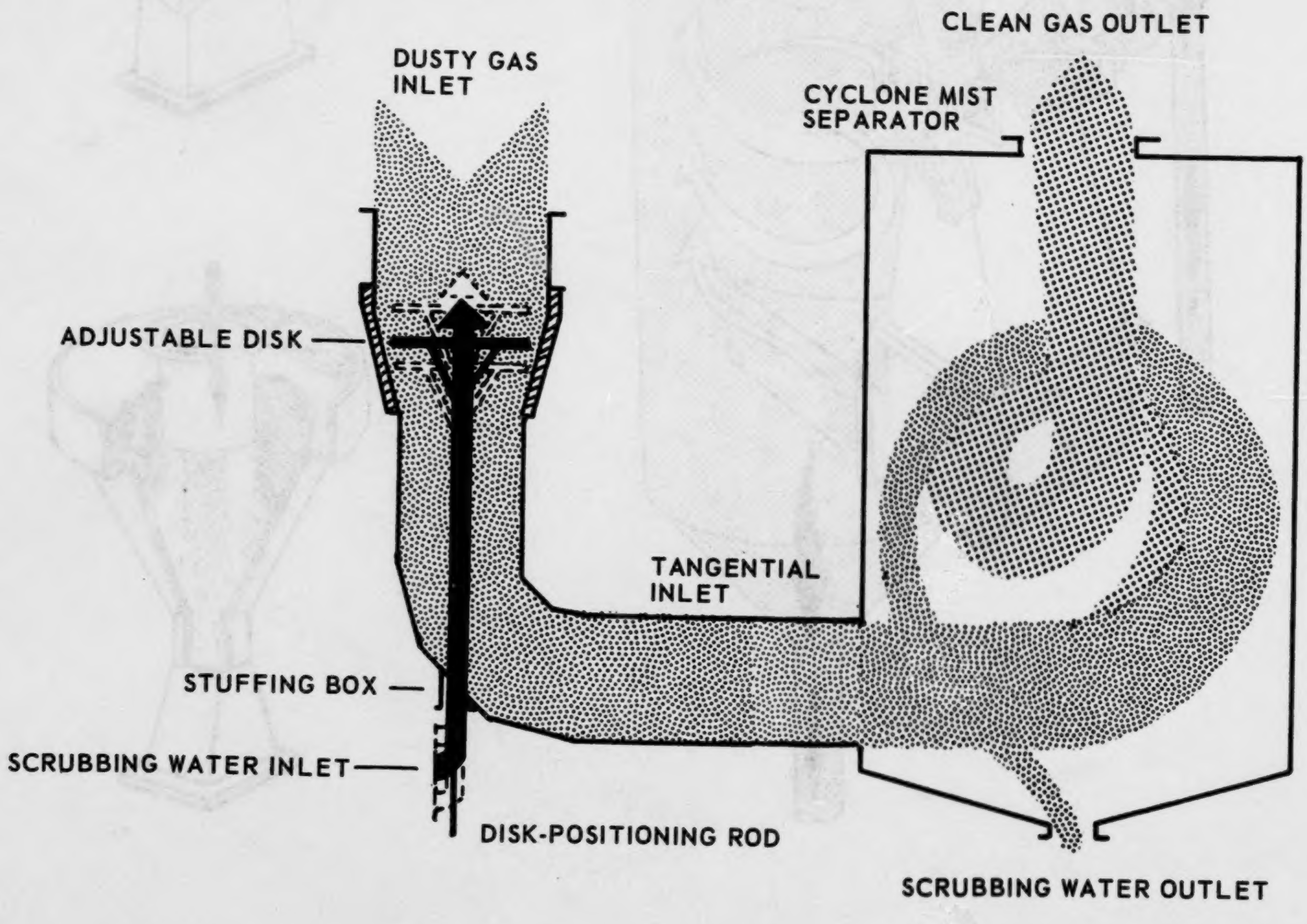


FIGURE 4-19. Flooded disk (variable throat orifice) scrubber.
(Courtesy of Research Cottrell Incorporated)

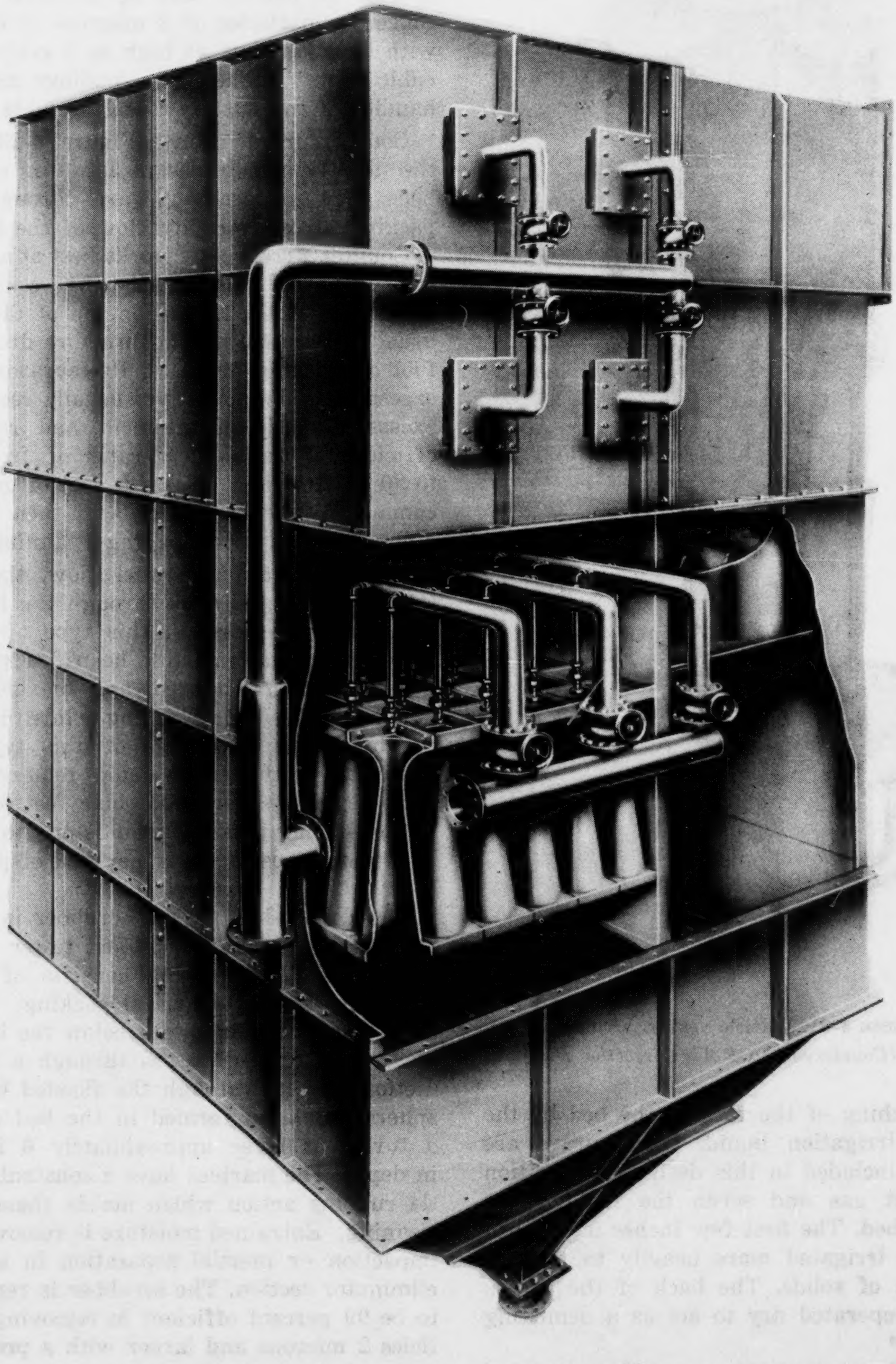


Figure 4–20. Multiple-venturi jet scrubber.

(Courtesy of Buell Corporation)

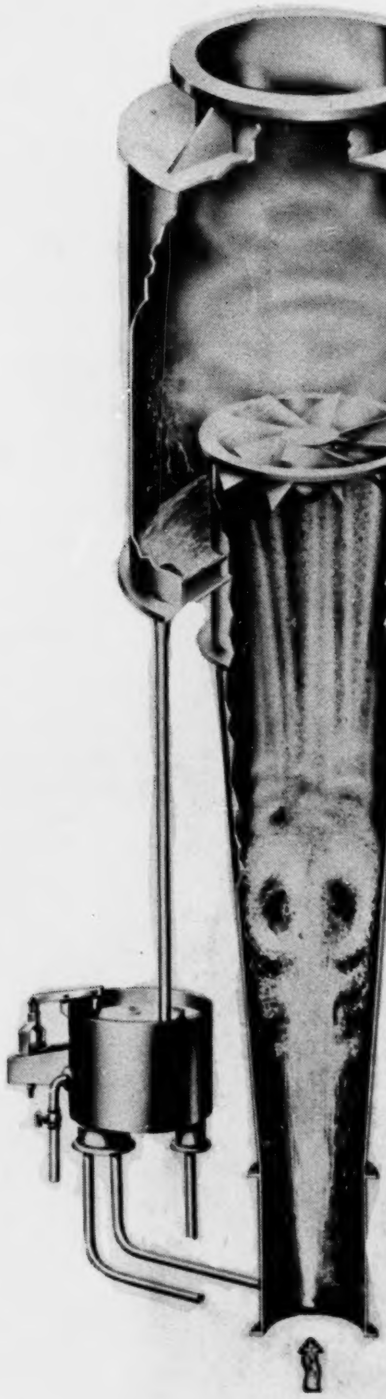


Figure 4–21. Verticle venturi scrubber.
(Courtesy of UOP Air Correction Division)

and washing of the face of the bed by the falling irrigation liquid. Inlet sprays are usually included in this design to condition the inlet gas and scrub the face of the packed bed. The first few inches of the bed may be irrigated more heavily to prevent build-up of solids. The back of the bed is usually operated dry to act as a demisting section.[46]

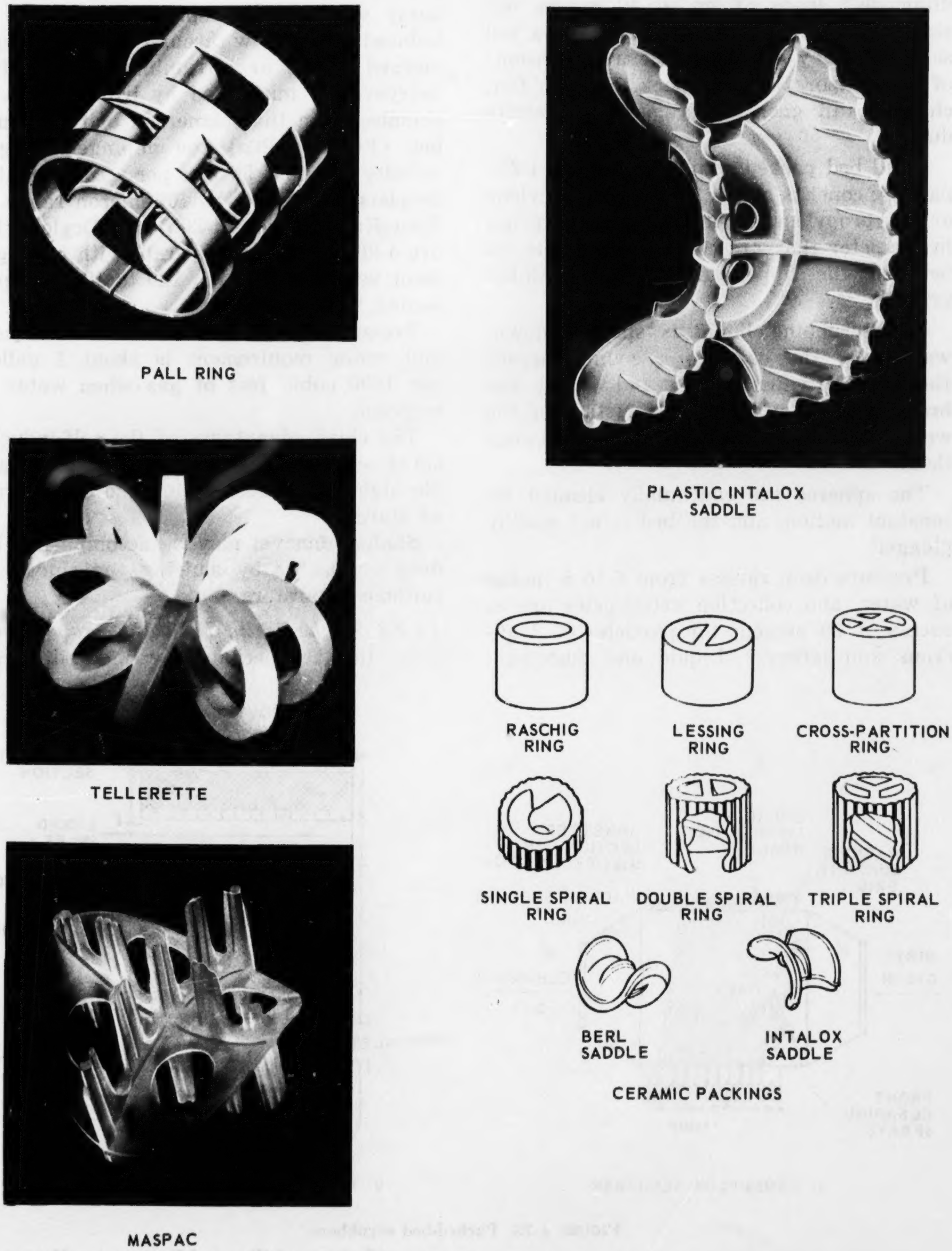
Liquid requirements range from 1 to 4 gallons per 1000 cubic feet of gas, with pressure drops of from 0.2 to 0.5 inch of water per foot of bed. Collection efficiency in excess of 90 percent may be achieved when collecting particles of 2 microns or larger, with dust loadings as high as 5 grains per cubic foot.[47] Higher dust loadings may be handled if the dust is readily soluble.

Countercurrent flow (Figure 4-23b) is the most common design used in packed beds. Gas is forced upward through the packing against gravity flow of the liquid.

Countercurrent flow works best at a pressure drop and gas velocity that cause the buildup of water in and on top of the bed, usually 0.5 to 1.0 inch of pressure drop per foot of packing depth.[48] Pressure drop in excess of this amount will usually result in excessive liquid entrainment and reduced efficiency. Liquid flow rates of from 10 to 20 gallons per 1000 cubic feet of gas are common. Water efficiency will then be at a maximum and bed clogging at a minimum.

In cocurrent, or parallel flow, the gas stream and liquid pass through the bed in the same direction. In this type of operation the irrigation liquid keeps the packed bed from being clogged, and the gas and liquid both assist in washing solids through the bed. The advantage of this type of operation is the small liquid requirement, 7 to 15 gallons per 1000 cubic feet of gas. The operating pressure drop is on the order of 1 to 4 inches of water per foot of packed bed.

The flooded-bed packed scrubber is operated as a counterflow packed tower (Figure 4-24). The packing consists of a 6-inch thick bed of spherical packing. Dust- and fume-laden air enters below the bed of glass marbles and passes through a spray section and up through the flooded bed of spheres. Bubbles formed in the bed create a turbulent layer approximately 6 inches in depth. The marbles have a constant, gentle rubbing action which makes them self-cleaning. Entrained moisture is removed by impaction or inertial separation in a mist eliminator section. The scrubber is reported to be 99 percent efficient in removing particles 2 microns and larger with a pressure drop of from 4 to 6 inches of water.[49]



PALL RING

TELLERETTE

MASPAC

PLASTIC INTALOX SADDLE

RASCHIG RING
LESSING RING
CROSS-PARTITION RING
SINGLE SPIRAL RING
DOUBLE SPIRAL RING
TRIPLE SPIRAL RING
BERL SADDLE
INTALOX SADDLE

CERAMIC PACKINGS

FIGURE 4-22. Wet scrubber packings.

Scrubbing liquid requirements are from 2 to 2½ gallons per 1000 cubic feet of gas. Liquid with a high solid content can be recirculated. The scrubber is capable of handling dust loads of up to 40 grains per standard cubic foot. Flooded bed packed scrubbers may be used to control emissions of acid vapors, carbon black, ceramic frit, chlorine tail gas, cupola gas, and ferrite dusts.

Fluid bed packed scrubber (Figure 4-25) packing consists of low density polyethylene or polypropylene spheres about 1½ inches in diameter that are continually in motion between the upper and lower retaining grid. [45]

The scrubbing liquid is sprayed downward over the balls in a countercurrent flow of dirty gas. Gas and liquid are brought into contact on the surface of the wetted spheres and in the spray between them.

The spheres are continually cleaned by constant motion, and the bed is not readily plugged.

Pressure drop ranges from 6 to 8 inches of water, and collection efficiencies are in excess of 99 percent for particles of 2 microns and larger.[49] Liquid and dust handling capacities are comparable to the flooded bed packed scrubber. [45]

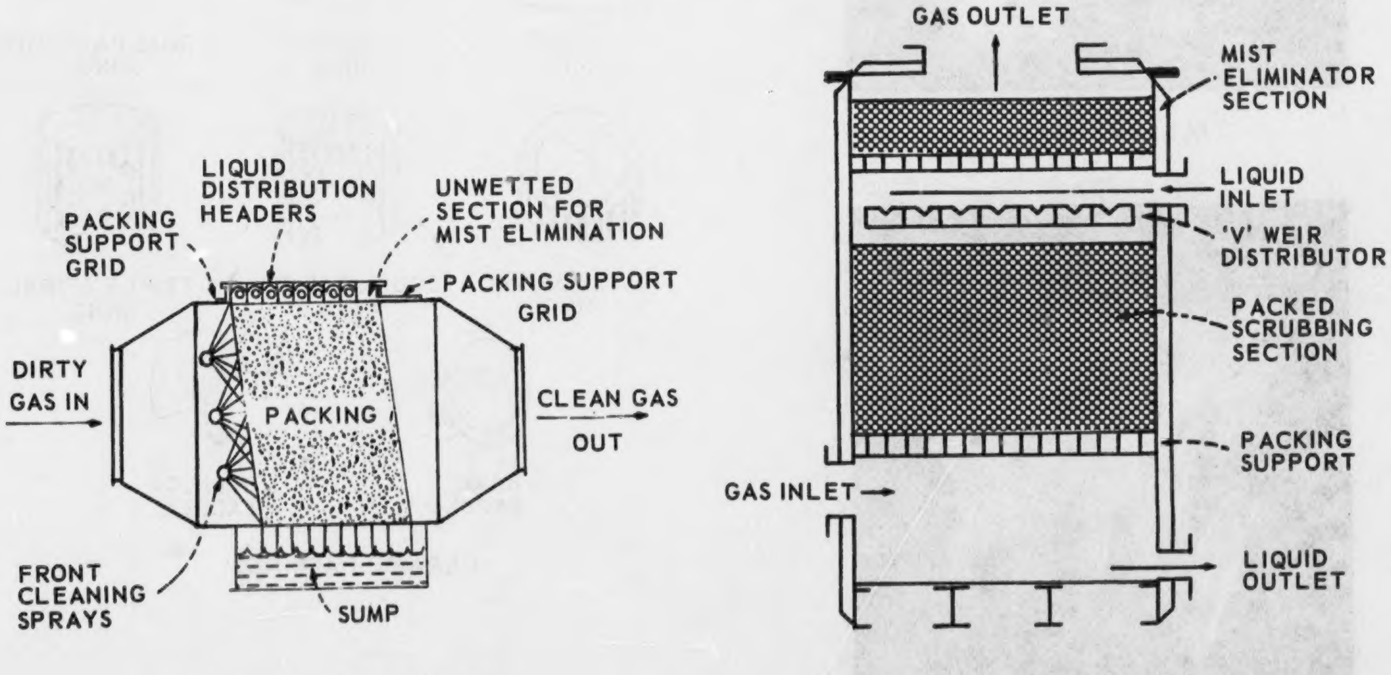
4.4.2.7 Self-Induced Spray Scrubbers.—The particle collection zone of the self-induced spray scrubber is a spray curtain that is induced by gas flow through a partially submerged orifice or streamlined baffle. Mist carryover is minimized by baffles or swirl chambers. In the submerged orifice scrubber (Figure 4-26a) the impingement gas velocity of about 50 feet per second creates droplets in the 300- to 400-micron range. [50] Blaw Knox (Figure 4-26b) and Doyle (Figure 4-26c) scrubbers operate with impingement velocities of from 120 to 180 feet per second. [51]

Pressure drop ranges from 2 to 15 inches, and water requirement is about 1 gallon per 1000 cubic feet of gas when water is recycled.

The chief advantages of the self-induced spray scrubber design are its ability to handle high dust concentration and concentrated slurries.

Sludge removal may be accomplished by drag chains or by sluicing the sludge to suitable separators.

4.4.2.8 Mechanically Induced Spray Scrubbers—In the mechanically induced spray


LIQUID DISTRIBUTION HEADERS
PACKING SUPPORT GRID
UNWETTED SECTION FOR MIST ELIMINATION
PACKING SUPPORT GRID
DIRTY GAS IN
PACKING
CLEAN GAS OUT
FRONT CLEANING SPRAYS
SUMP
GAS OUTLET
MIST ELIMINATOR SECTION
LIQUID INLET
'V' WEIR DISTRIBUTOR
PACKED SCRUBBING SECTION
PACKING SUPPORT
GAS INLET
LIQUID OUTLET

a. CROSS-FLOW SCRUBBER

b. COUNTERCURRENT-FLOW SCRUBBER

FIGURE 4-23. Packed-bed scrubbers.

(Courtesy of Chemical Engineering Magazine)

scrubber (Figures 4-27a and 4-27b) high-velocity sprays are generated at right angles to the direction of gas flow by a partially submerged rotor. Scrubbing is achieved by impaction because of both high radial droplet velocity and vertical gas velocity. Liquid atomization occurs at the rotor and at the outer wall.[52]

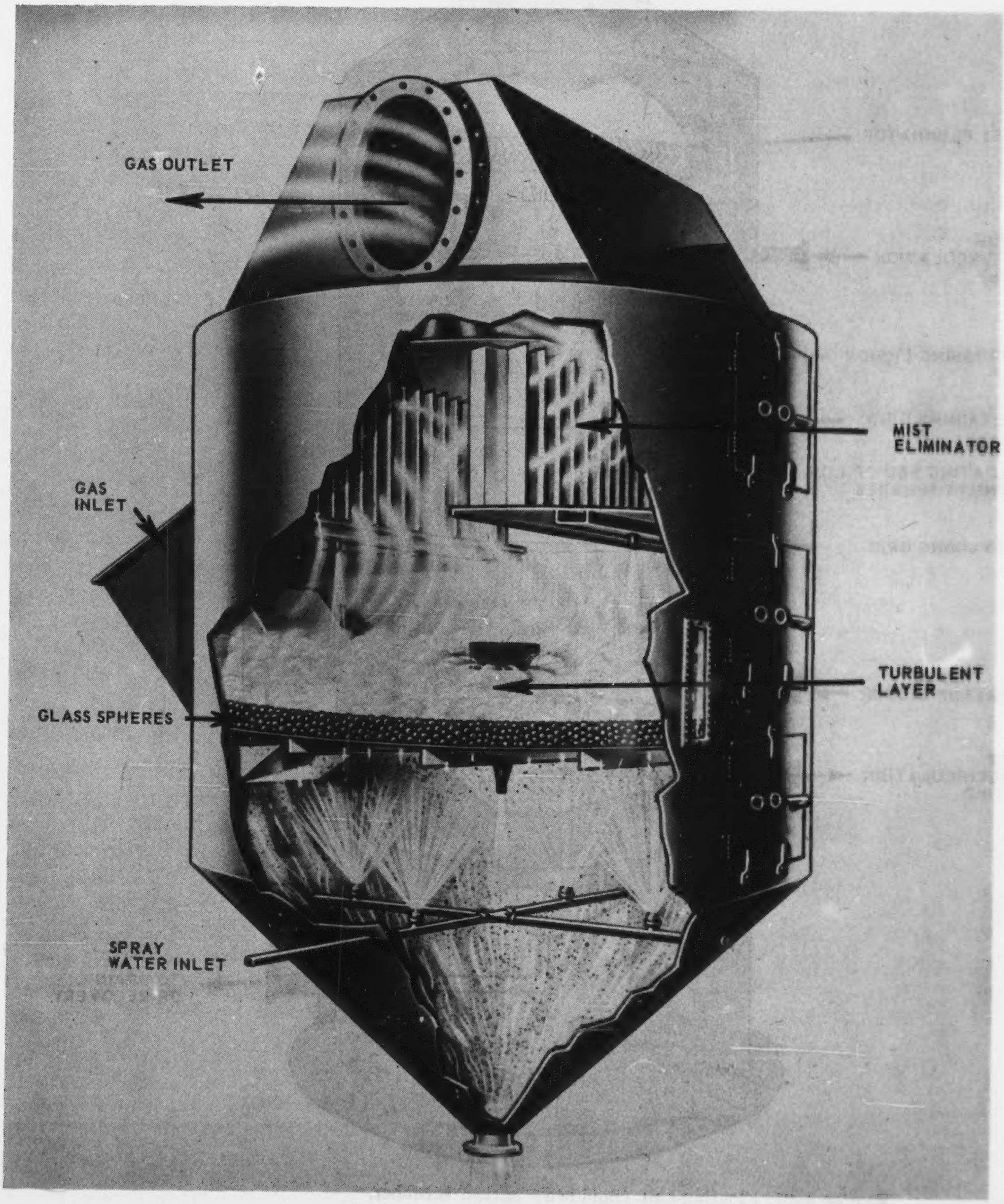

GAS OUTLET
MIST ELIMINATOR
GAS INLET
TURBULENT LAYER
GLASS SPHERES
SPRAY WATER INLET

FIGURE 4-24. Flooded-bed scrubber.
(Courtesy of National Dust Collector Corporation)

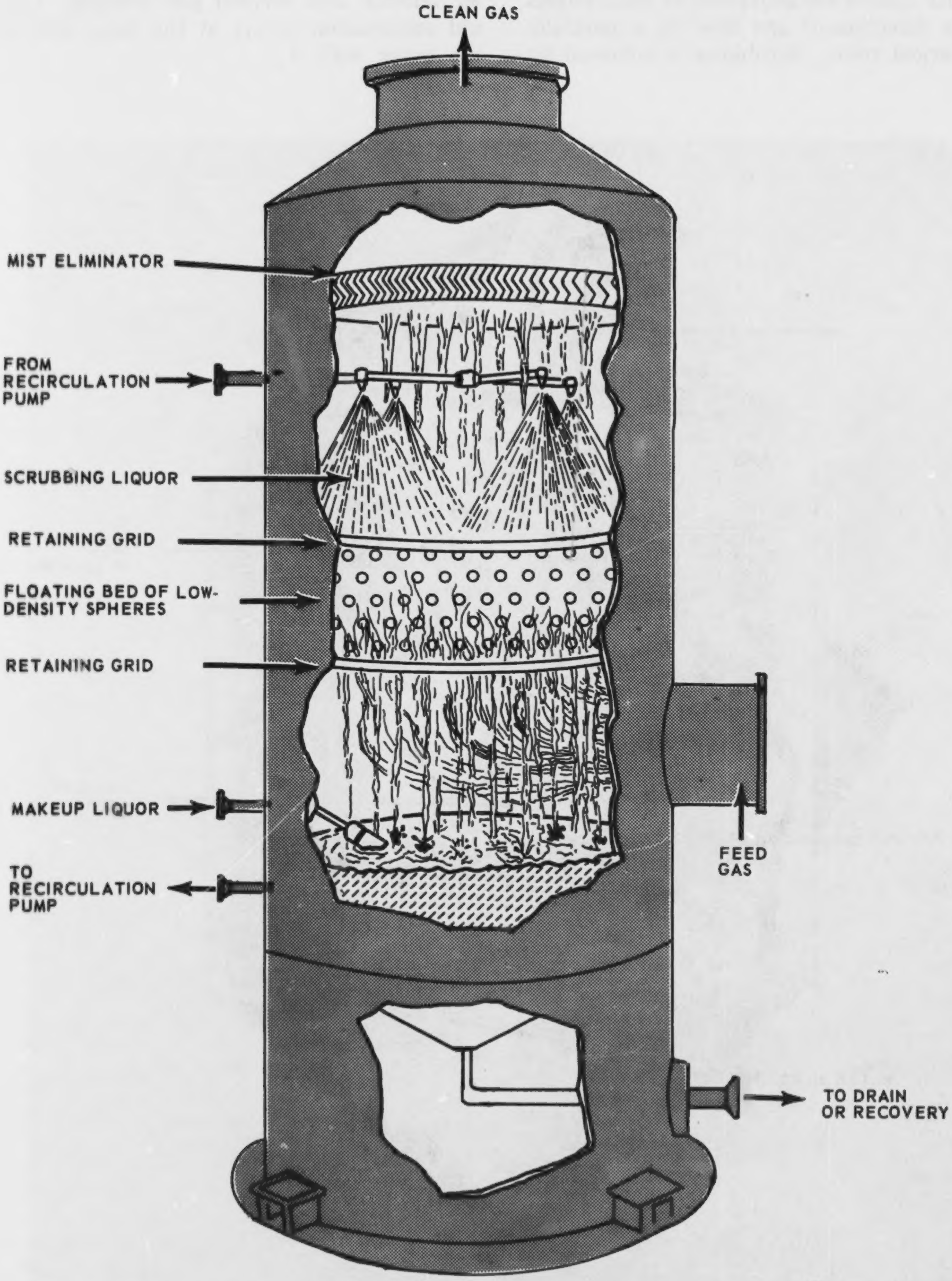
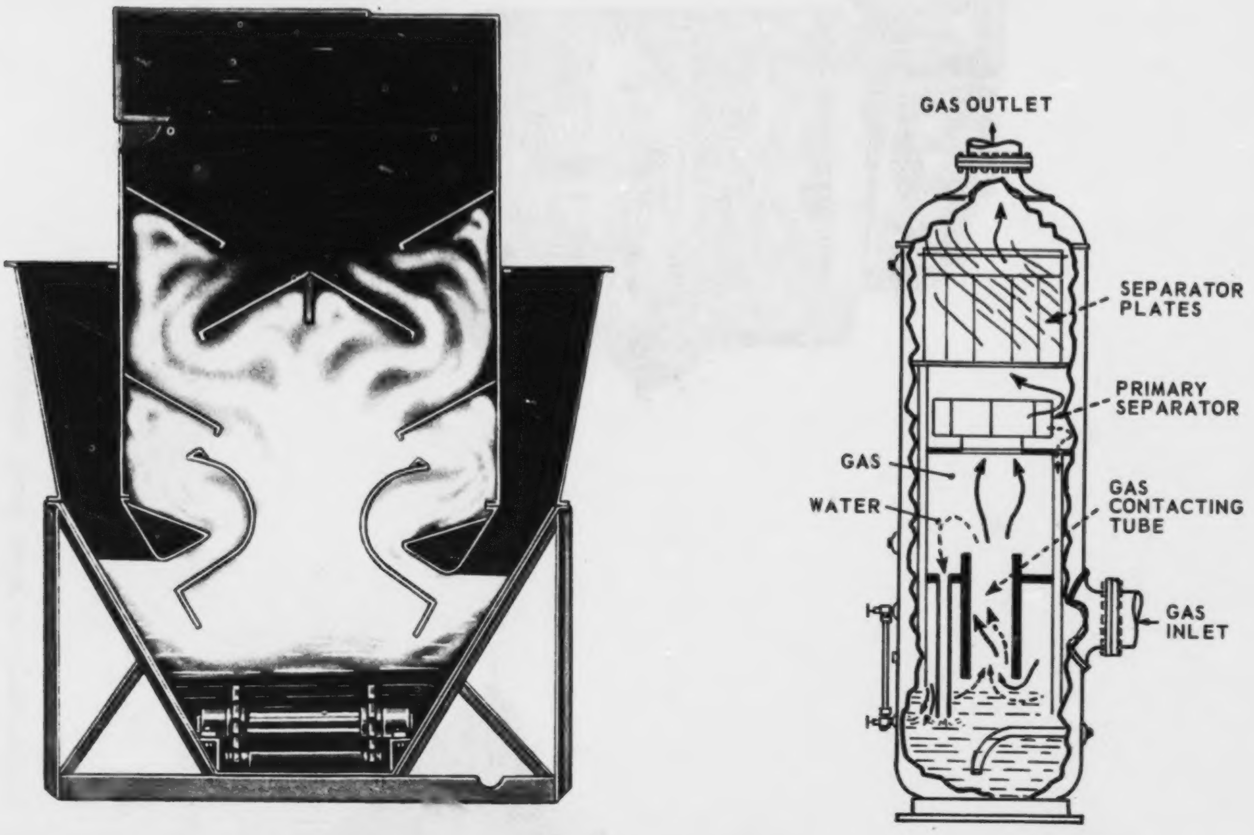
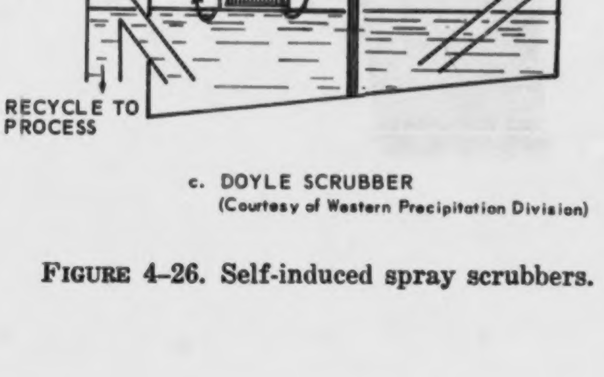

CLEAN GAS
MIST ELIMINATOR
FROM RECIRCULATION PUMP
SCRUBBING LIQUOR
RETAINING GRID
FLOATING BED OF LOW-DENSITY SPHERES
RETAINING GRID
MAKEUP LIQUOR
TO RECIRCULATION PUMP
FEED GAS
TO DRAIN OR RECOVERY

Figure 4-25. Floating-ball (fluid-bed) packed scrubber.
(Courtesy of UOP Air Correction Division)


GAS OUTLET
SEPARATOR PLATES
PRIMARY SEPARATOR
GAS
WATER
GAS CONTACTING TUBE
GAS INLET

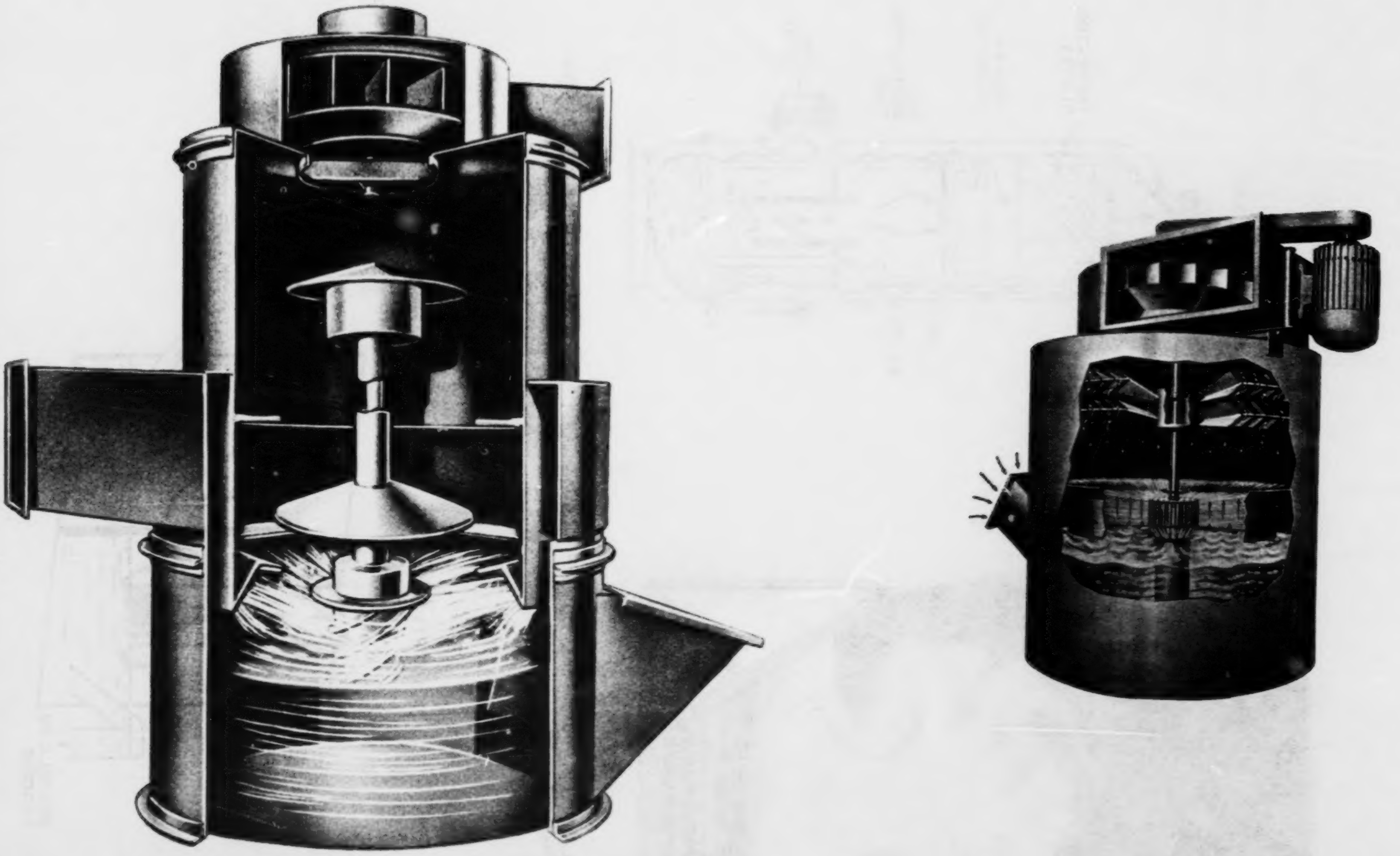
a. SCHMIEG SWIRL-ORIFICE DUST COLLECTOR
(Courtesy of United Sheet Metal Co., Inc.)

b. LIQUID VORTEX CONTRACTOR
(Courtesy of Blaw Knox Co.)


DIRTY GAS
CLEAN GAS
WATER
RECYCLE TO PROCESS

c. DOYLE SCRUBBER
(Courtesy of Western Precipitation Division)

Figure 4–26. Self-induced spray scrubbers.



a. SCHMIEG VERTICAL-ROTOR DUST COLLECTOR
(Courtesy of United Sheet Metal Co., Inc.)

b. CENTER SPRAY HIGH-VELOCITY SCRUBBER
(Courtesy of Air Engineering Magazine)

FIGURE 4–27. Mechanically induced spray scrubbers.

Power and liquid requirements range from 3 to 10 horsepower and from 4 to 5 gallons per 1000 cubic feet of gas for the high-velocity design (Figure 4-27b), depending on particle size and the desired level of scrubbing efficiency.[53]

Advantages of this type of scrubber are relatively low liquid requirements, small space requirements, high scrubbing efficiency, and high dust load capacity. The rotor, however, is susceptible to erosion from large particles and abrasive dusts, and high-energy scrubbing applications may require the use of additional mist elimination equipment.

4.4.2.9 Disintegrator Scrubbers—A disintegrator scrubber consists of a barred rotor

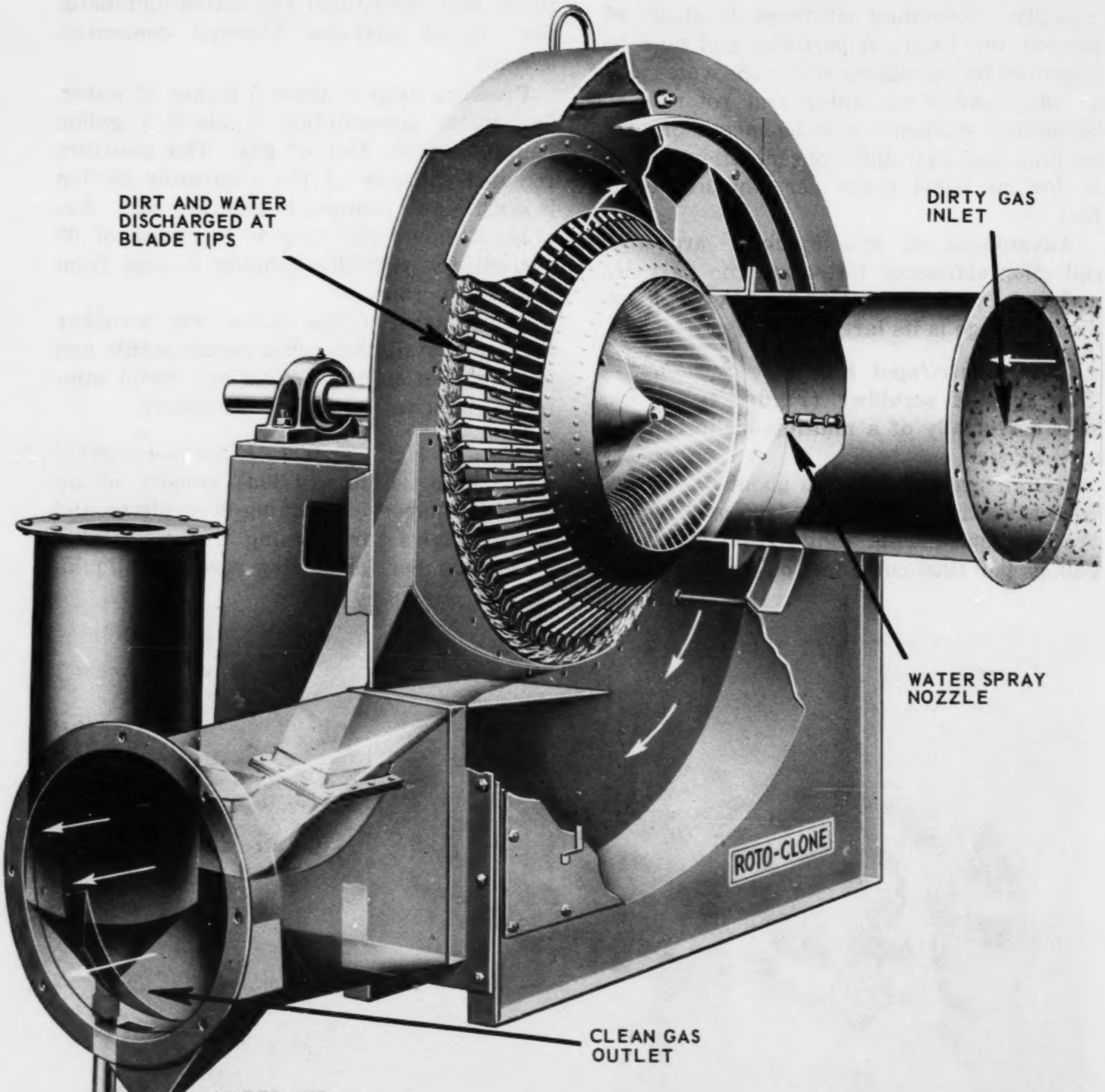

DIRT AND WATER DISCHARGED AT BLADE TIPS
DIRTY GAS INLET
WATER SPRAY NOZZLE
ROTO-CLONE
CLEAN GAS OUTLET
WATER AND SLUDGE OUTLET

Figure 4-28. Centrifugal fan wet scrubber.

(Courtesy of American Air Filter Company)

within a barred stator. Water is injected axially through the rotor shaft and is separated into fine droplets by the high relative velocity of rotor and stator bars. Dust particles are impacted by the high velocity liquid droplets.

Water and power requirements range from 4 to 9 gallons per minute and from 7 to 11 horsepower, respectively, for each 1000 cubic feet per minute of gas handling capacity. Scrubbing efficiency is about 95 percent for 1-micron particles and may be improved by increasing either the water rate or the number of stator and rotor bars. Scrubbing efficiency is independent of dust loading, and exit dust concentrations range as low as 0.004 grain per standard cubic foot.[54]

Advantages of this scrubber are high collection efficiency for submicron particles and low space requirements. The principal disadvantage is its large power requirement.

4.4.2.10 Centrifugal Fan Wet Scrubbers—This type of scrubber (Figure 4-28) consists essentially of a multiple-blade centrifugal blower.

Design pressure drop is about 6½ inches with a maximum pressure drop of 9 inches. Water requirements range from ¾ to 1.5 gallons per 1000 cubic feet of gas and power requirements range from 1 to 2 horsepower per 1000 cubic feet per minute.[55]

The chief advantages are low space requirements, moderate power requirements, low water consumption, and a relatively high scrubbing efficiency.

4.4.2.11 Inline Wet Scrubbers—In this axial-fan-powered gas scrubber (Figure 4-29), a water spray and baffle screen wet the particles, and centrifugal fan action eliminates the wetted particles through concentric louvers.

Pressure drop is about 5 inches of water, and water consumption is about 1 gallon per 1000 cubic feet of gas. The moisture removal capacity of the eliminator section is sensitive to changes in gas flow rate. Average removal efficiency is in excess of 99 percent for particles ranging in size from 5 to 10 microns.[56]

Advantages of the inline wet scrubber are low installation space requirements and low installation costs. Coal and metal mining industries use inline scrubbers.

4.4.2.12 Irrigated Wet Filters—Irrigated wet filters (Figure 4-30a) consist of an upper chamber, containing wet filters and spray nozzles for cleaning the gas, and a lower chamber for storing scrubbing liquid.

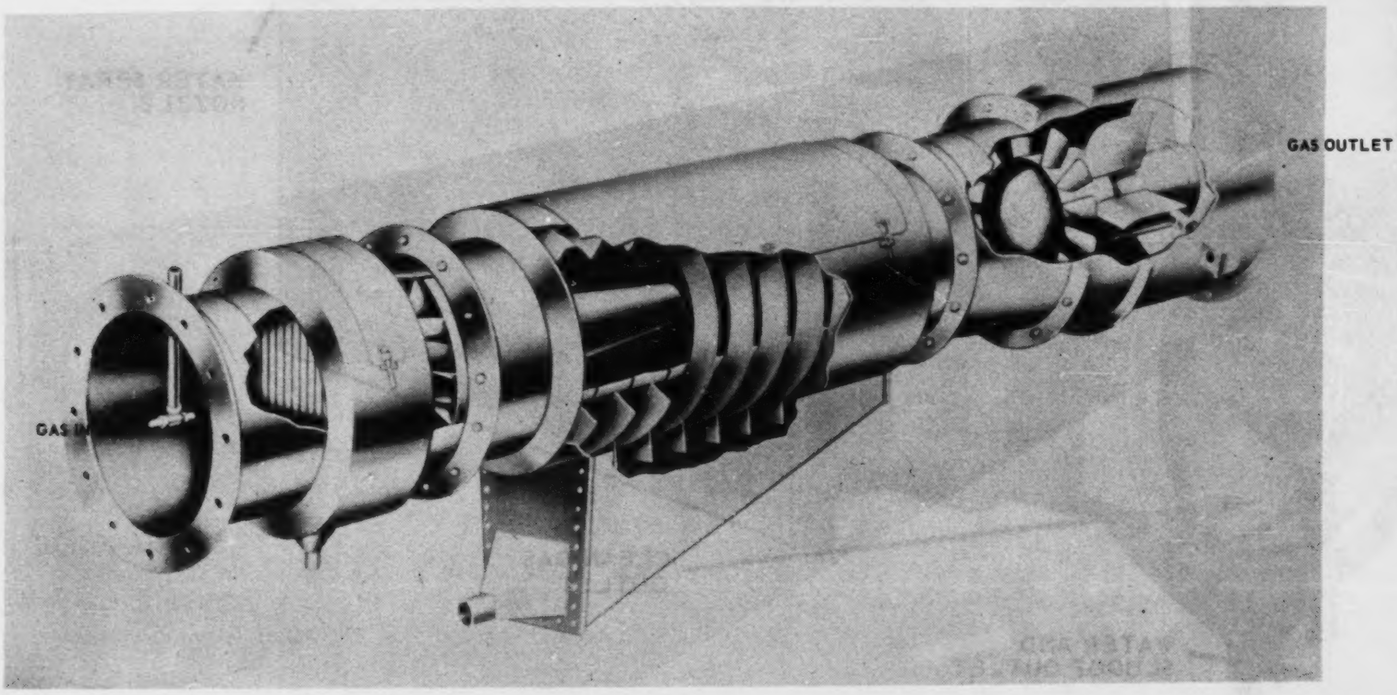
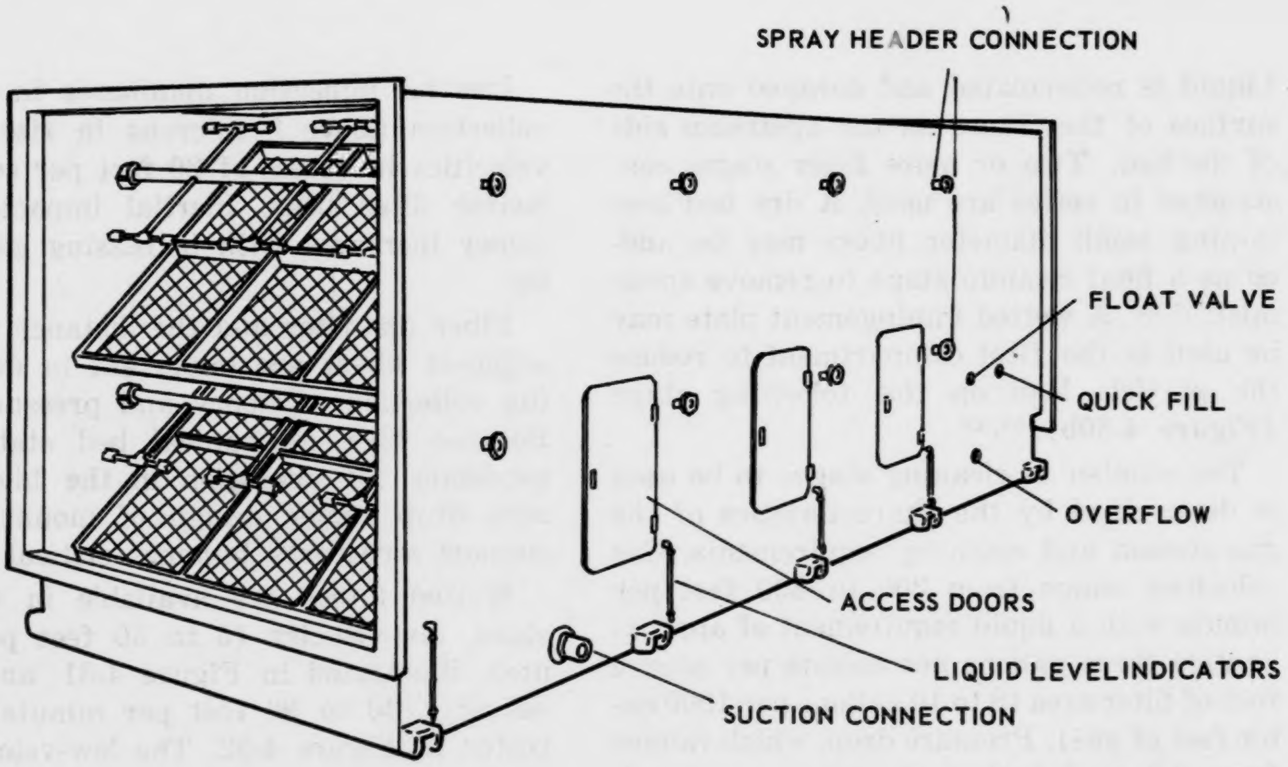
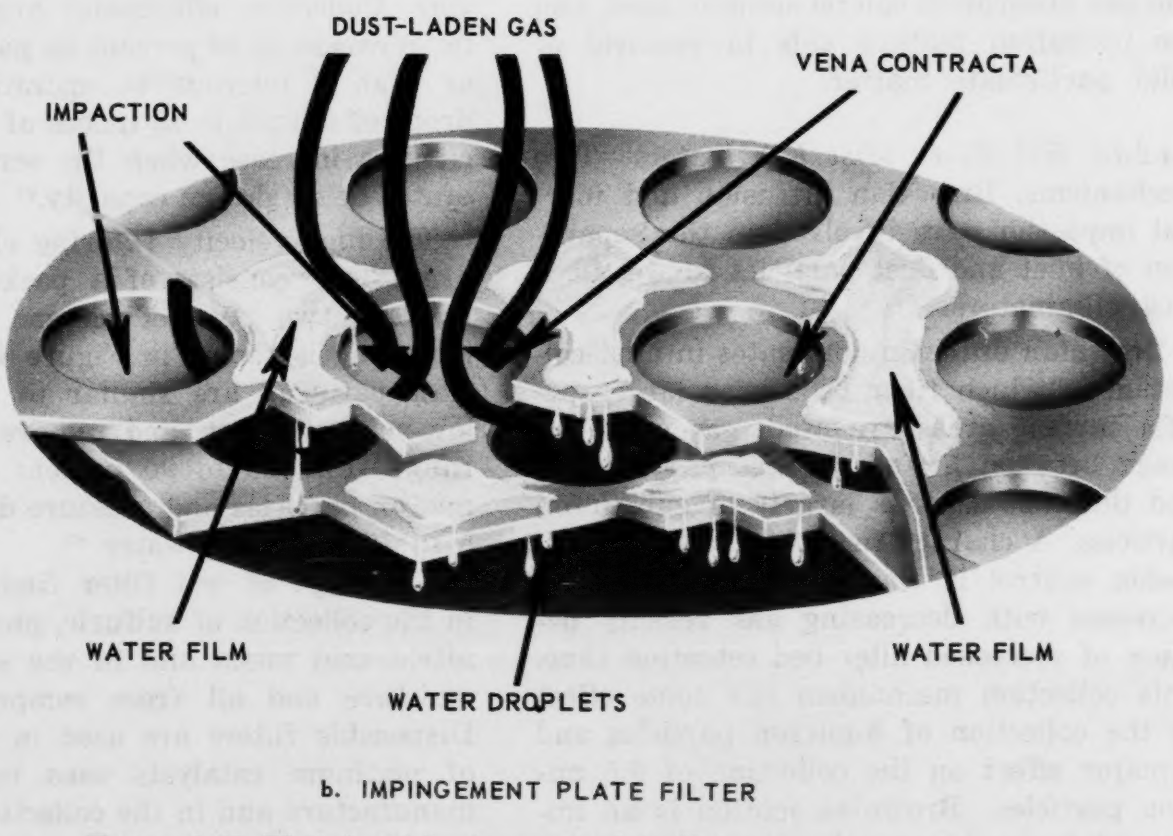


FIGURE 4-29. Inline wet scrubber.

(Courtesy of Joy Manufacturing Company)


SPRAY HEADER CONNECTION
FLOAT VALVE
QUICK FILL
OVERFLOW
ACCESS DOORS
LIQUID LEVEL INDICATORS
SUCTION CONNECTION

a. WETTED FILTER


DUST-LADEN GAS
VENA CONTRACTA
IMPACTION
WATER FILM
WATER FILM
WATER DROPLETS

b. IMPINGEMENT PLATE FILTER

FIGURE 4-30. Wetted and impingement plate filters.

(Courtesy of Buffalo Forge Company)

Liquid is recirculated and sprayed onto the surface of the filters on the upstream side of the bed. Two or more filter stages constructed in series are used. A dry bed containing small diameter fibers may be added as a final cleanup stage to remove spray mist.[57, 58] A wetted impingement plate may be used in the first compartment to reduce the particle load on the following stage (Figure 4-30b).[59, 60]

The number of cleaning stages to be used is determined by the characteristics of the gas stream and cleaning requirements. Gas velocities range from 200 to 300 feet per minute with a liquid requirement of approximately three gallons per minute per square foot of filter area (8 to 10 gallons per 1000 cubic feet of gas). Pressure drop, which ranges from 0.2 to 3 inches of water per 4-inch bed depth, is dependent on the gas loading, liquid loading, and fiber bed density. Normal bed thickness may range from 1 to 4 inches, based on scrubbing requirements.[57]

The chief mechanism of irrigated wet filters involved in the capture of particulate matter is interception by individual filaments in the filter. Both particle removal and gas absorption can be accomplished, and the irrigation feature aids in removal of solid particulate matter.

4.4.2.13 Wet Fiber Mist Eliminators—Two mechanisms, Brownian diffusion and inertial impaction, are involved in the separation of mist and dust particles in wet fiber mist eliminators.

Brownian diffusion dominates in mist collection in which fiber beds with large specific surface areas are used, gas velocities range between 5 and 30 feet per minute, and the mist consists largely of submicron particles. A characteristic of Brownian diffusion control is that collection efficiency increases with decreasing gas velocity because of increased filter bed retention time. This collection mechanism has some effect on the collection of 3-micron particles and a major effect on the collection of 0.5 micron particles. Brownian motion is an important factor in particle capture by direct interception.

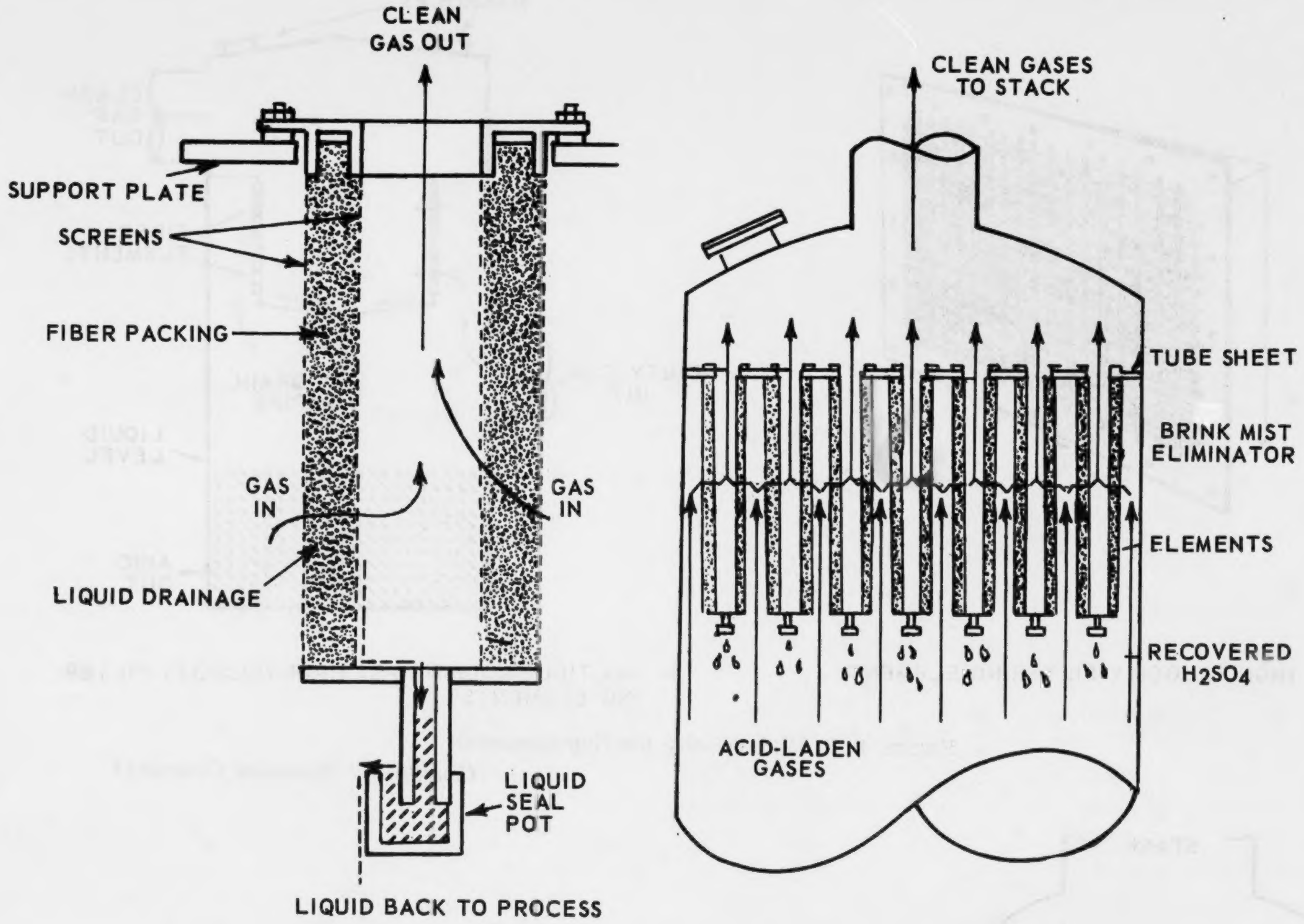
Inertial impaction dominates in particle collection above 3 microns in size at gas velocities in excess of 30 feet per second in coarse filter beds. Inertial impaction efficiency increases with increasing gas velocity.

Fiber diameter and the distance between adjacent fibers are important in determining collection efficiency and pressure drop. Because high mechanical bed stability is necessary for operation in the high pressure drop range, design of mounting and support structures becomes critical.[56]

Wetted filters are available in two designs, low-velocity (5 to 30 feet per minute), illustrated in Figure 4-31, and high-velocity (30 to 90 feet per minute), illustrated in Figure 4-32. The low-velocity design consists of a packed bed of fibers retained between two concentric screens. Mist particles collect on the surface of the fibers, coalesce to form a liquid film that wets the fibers, and are moved horizontally and downward by gravity and the drag of the gases. The liquid flows down the inner screen to the bottom of the element and through a liquid seal to a collection reservoir. Collection efficiencies are reported to be in excess of 99 percent on particles smaller than 3 microns at operating pressure drops of from 5 to 15 inches of water. Efficiencies increase when the scrubber is operated below design capacity.[61]

The high-velocity filtering element (Figure 4-32a) consists of a packed fiber bed between two parallel screens. A multiple mounting is shown in Figure 4-32b. Liquid flow patterns are similar to those of the low-velocity filter, and removal efficiencies range from 85 to 90 percent for 1- to 3-micron particles and pressure drops of from 5 to 10 inches of water.[62]

This type of wet filter finds application in the collection of sulfuric, phosphoric, and nitric acid mists and in the separation of moisture and oil from compressed gases. Disposable filters are used in the recovery of platinum catalysts used in nitric acid manufacture and in the collection of viruses and bacteria, and radioactive and toxic dusts.[63]


CLEAN GAS OUT
SUPPORT PLATE
SCREENS
FIBER PACKING
GAS IN
GAS IN
LIQUID DRAINAGE
LIQUID SEAL POT
LIQUID BACK TO PROCESS
CLEAN GASES TO STACK
TUBE SHEET
BRINK MIST ELIMINATOR
ELEMENTS
RECOVERED H2SO4
ACID-LADEN GASES

a. LOW-VELOCITY FILTERING ELEMENT

b. MULTIPLE MOUNTING OF LOW-VELOCITY FILTERING ELEMENTS

FIGURE 4-31. Low-velocity filtering elements.

(Courtesy of Monsanto Company)

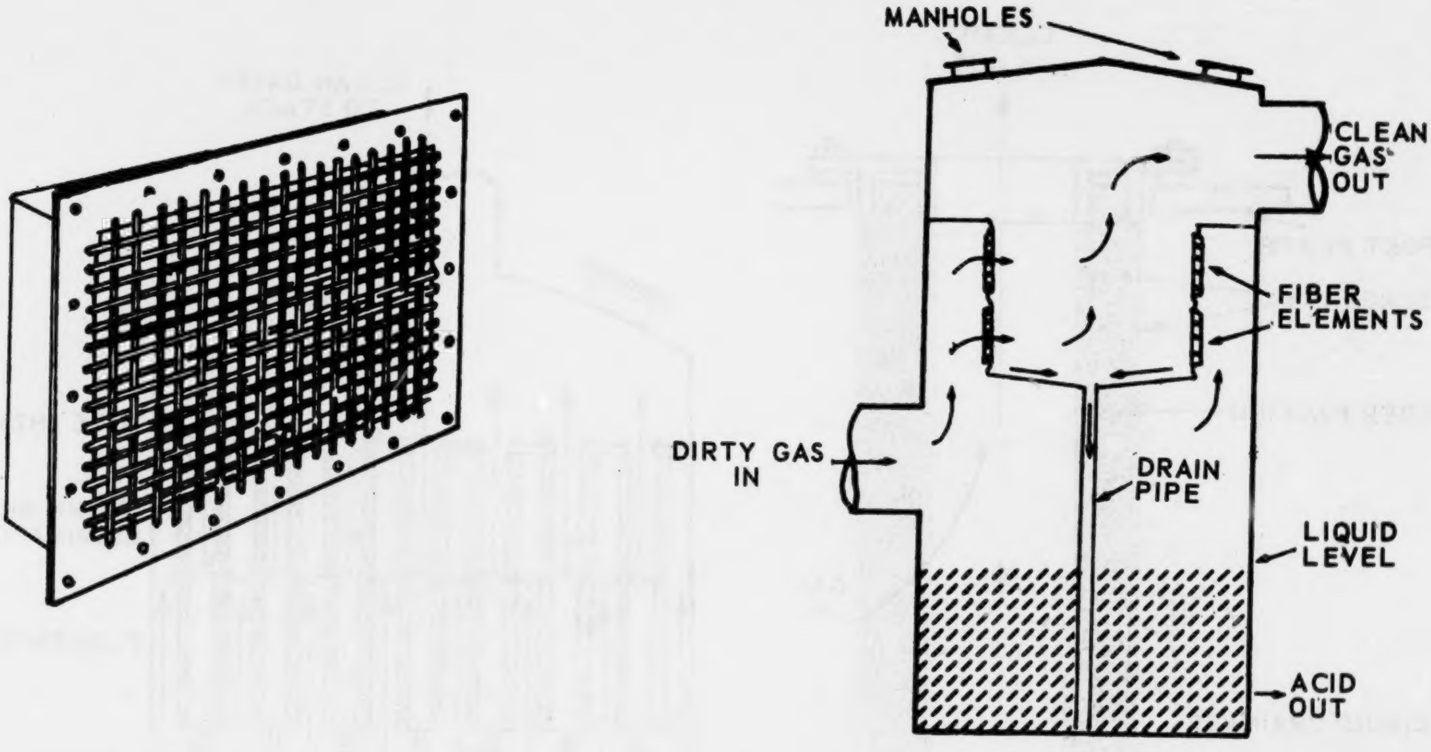
The wire mesh filter consists of an evenly spaced knitted wire mesh and is usually mounted in horizontal beds (Figure 4-33). The principal collection mechanism is inertial impaction. Rising mist droplets strike the wire surface, flow down the wire to a wire junction, coalesce, and flow to the bottom surface of the bed, where the liquid disengages in the form of large droplets and returns by gravity to the process equipment. [64]

Operating pressure drop is usually less than 1 inch of water with gas velocities of from 10 to 15 feet per second. Recent development has centered on the area of high energy filtration in which pressure drops of from 35 to 40 inches of water gauge have been used.

Factors governing maximum allowable gas velocities include gas and liquid density, surface tension, viscosity, bed specific surface area, liquid loading, and suspended solids content. [64]

Advantages in the use of fiber filters and wire mesh mist collectors are high removal efficiency, simplicity of operation, low maintenance in dust-free service, low initial cost, and recovery of valuable products without dilution.

4.4.2.14 Impingement Baffle Mist Eliminators—Baffle mist eliminators offer one of the simplest methods of controlling large-diameter solid and liquid particulate emissions. A variety of designs are in use. Figure 4-34 shows the arrangement of baffles

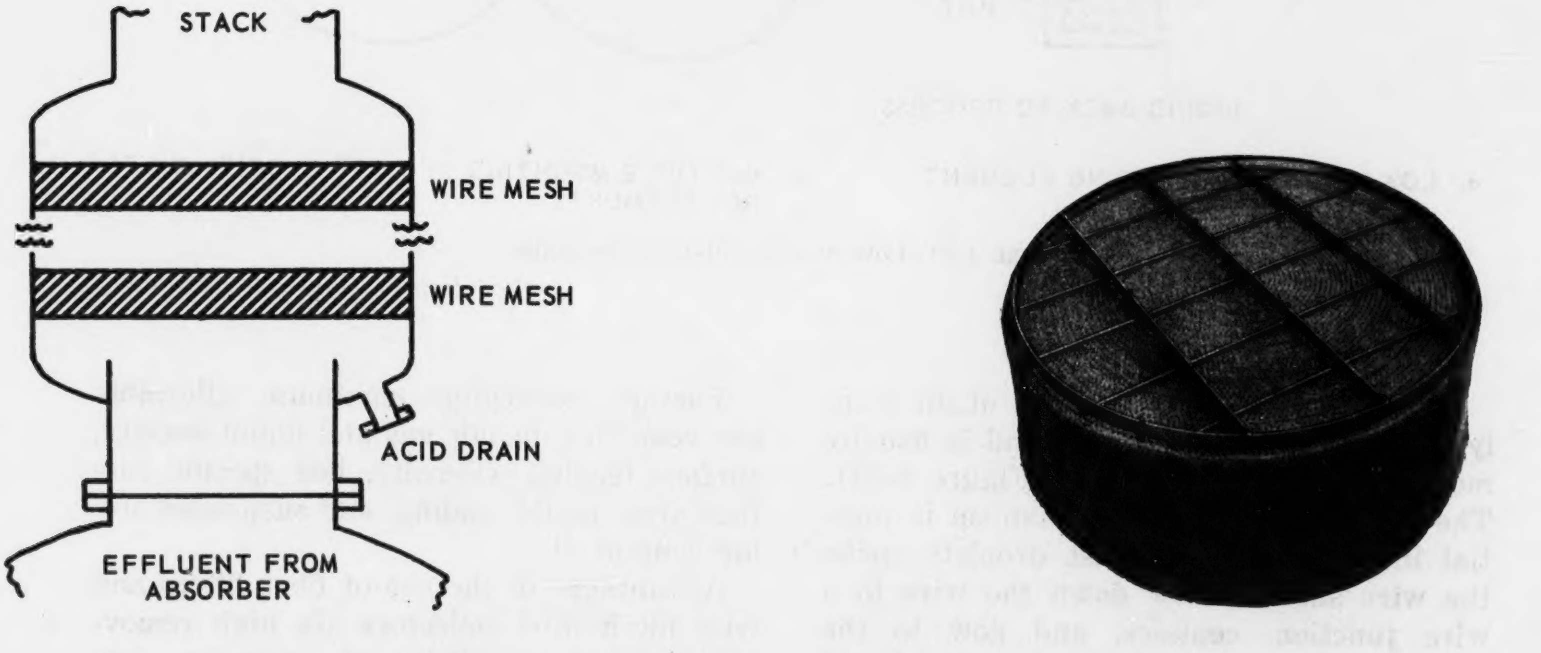

MANHOLES
CLEAN GAS OUT
FIBER ELEMENTS
DIRTY GAS IN
DRAIN PIPE
LIQUID LEVEL
ACID OUT

a. HIGH-VELOCITY FILTERING ELEMENT

b. MULTIPLE MOUNTING OF HIGH-VELOCITY FILTERING ELEMENTS

FIGURE 4–32. High-velocity filtering elements.

(Courtesy of Monsanto Company)

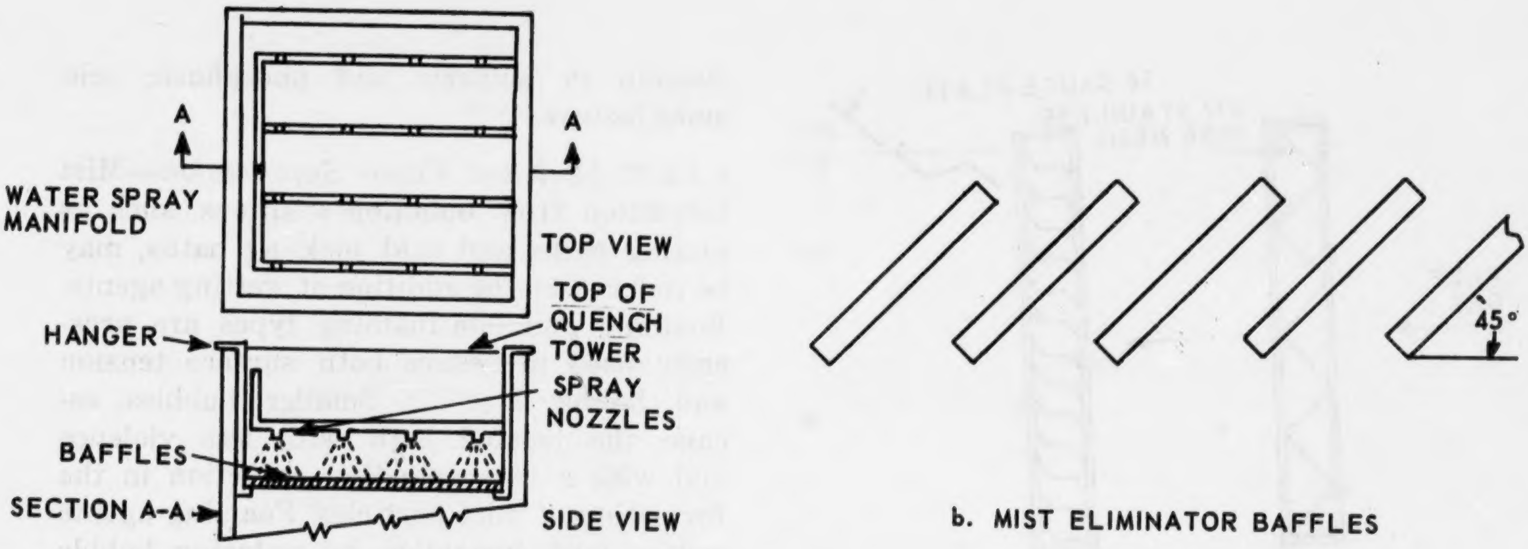

STACK
WIRE MESH
WIRE MESH
ACID DRAIN
EFFLUENT FROM ABSORBER

a. MIST ELIMINATOR ARRANGEMENT IN VESSEL ABOVE ACID PLANT ABSORBER
(Courtesy of Chemical Engineering Progress Magazine)

b. ONE-PIECE DEMISTER®
(Courtesy of Otto H. York Co., Inc.)

FIGURE 4–33. Wire mesh mist eliminators.

successfully used in the reduction of emissions from coke quenching operations.[65] An 85 to 90 percent reduction of emissions was achieved on particulate matter which ranged from 16 to 200 mesh at gas velocities ranging to a high of 36 feet per second. A significant


A
A
WATER SPRAY MANIFOLD
TOP VIEW
TOP OF QUENCH TOWER
HANGER
SPRAY NOZZLES
BAFFLES
SECTION A-A
SIDE VIEW
45°

a. DIAGRAM OF BAFFLE SYSTEM SHOWING CLEANING WATER SPRAYS AND BAFFLE ARRANGEMENT

b. MIST ELIMINATOR BAFFLES

FIGURE. 4-34. Coke quench mist elimination baffle system.

(Courtesy of U.S. Steel Corp.)

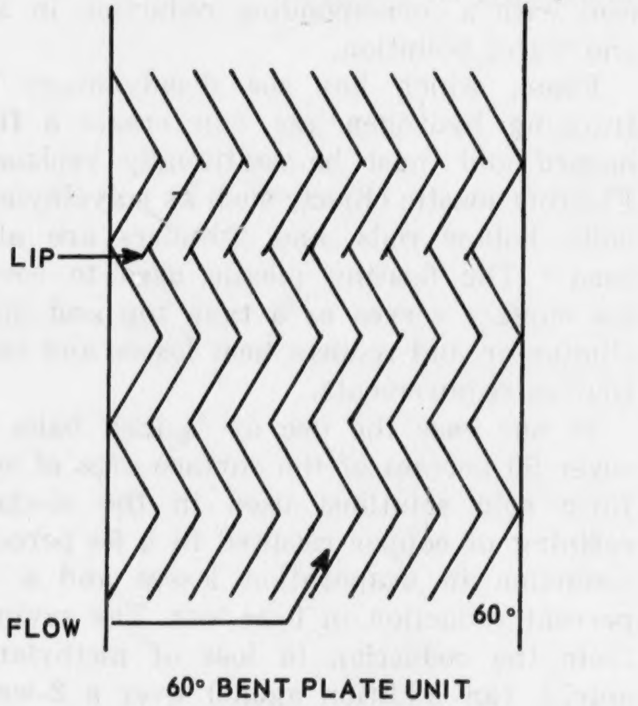

LIP
FLOW
60°
60° BENT PLATE UNIT

FIGURE 4-35. Details of baffle design.

(Courtesy of Chemical Engineering Progress Magazine)

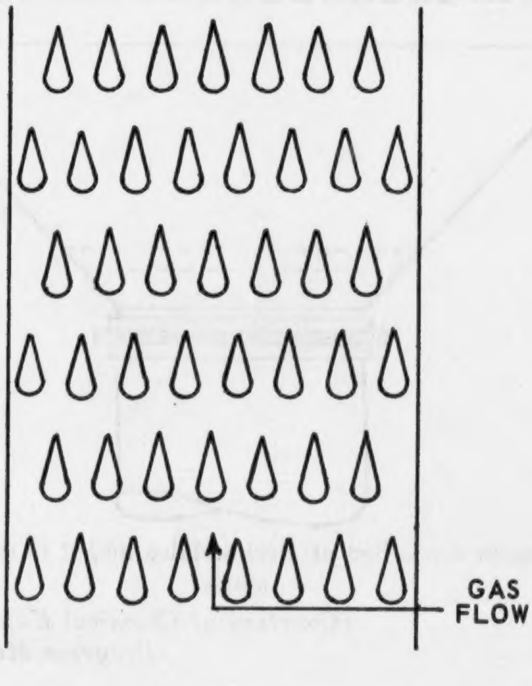


FIGURE 4-36. Streamline mist eliminator baffles.

reduction in water droplet fallout was also achieved. The baffles were operated dry with short spray periods to prevent the buildup of solids.[65] Figures 4-35, 4-36, and 4-37 show the common layouts of mist eliminator baffles used in spray chamber scrubbers.[35, 36] Mist removal efficiencies of as high as 95 percent may be achieved for the removal of 40-micron spray droplets up to a maximum gas velocity of 25 feet per second and pressure drops of from 1 to 2 inches of water. Velocities in excess of 25 feet per second result in the re-entrainment of liquid droplets.

4.4.2.15 Vane-Type Mist Eliminators—Vane-type mist eliminators have a range of operation of from 10 to 50 feet per second, with collection efficiencies reported to be as high as 99 percent for 11-micron particles and with pressure drops from 0.1 to 2 inches of water. The principal advantage of vane type

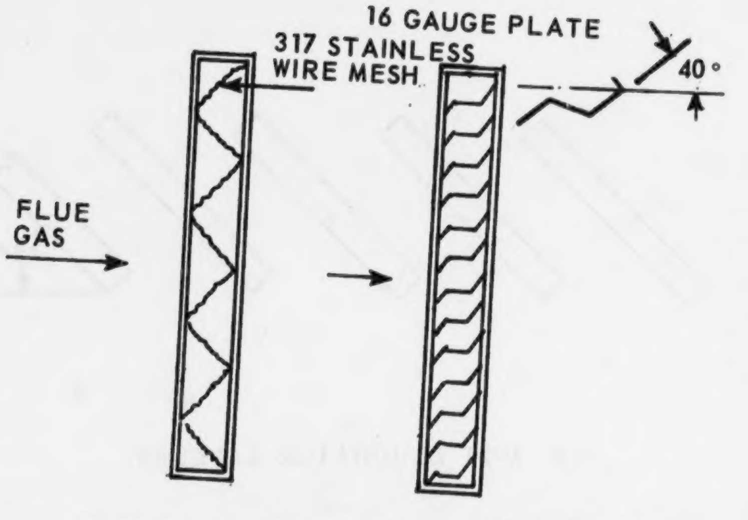


Figure 4-37. Screen and mist eliminator details. *(Courtesy of Paper Trade Journal)*

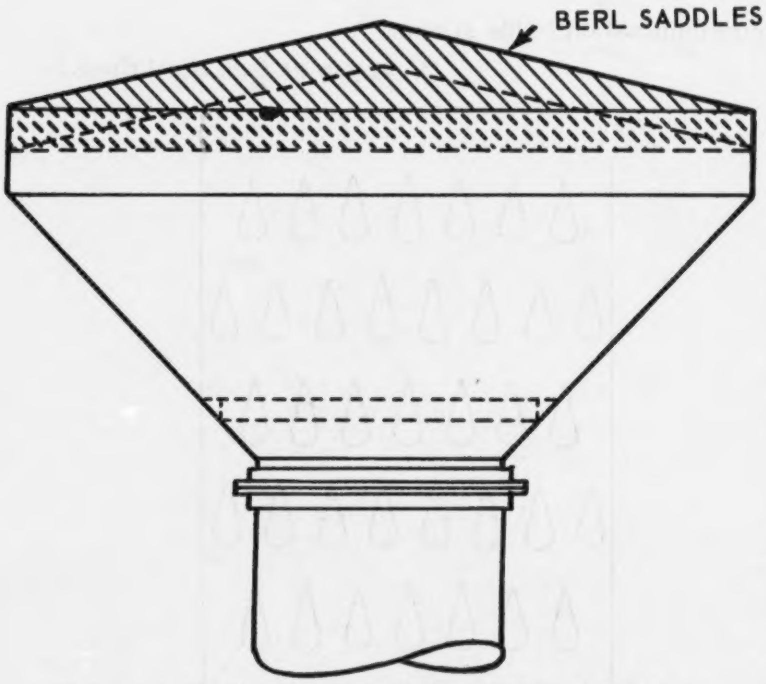


Figure 4-38. Bed of Berl saddles added to discharge stack. *(Courtesy of Chemical Engineering Progress Magazine)*

over baffle mist eliminators is the wider range of operation at comparable collection efficiencies.[67]

4.4.2.16 Packed Bed Mist Eliminators—Figure 4-38 shows a packed bed stack mist eliminator. Removal efficiencies of such devices may range to as high as 65 percent at gas velocities from .7 to 10 feet per second. Mist re-entrainment occurs at higher gas velocities because of the turbulent nature of gas flow in packed beds. This type of mist eliminator is often used for tail gas cleanup in sulfuric and phosphoric acid manufacture. [68-70]

4.4.2.17 Mist and Vapor Suppression—Mist formation from bubbling solutions, such as plating baths and acid pickling baths, may be reduced by the addition of wetting agents. Foaming and non-foaming types are presently used to reduce both surface tension and bubble size.[71-74] Smaller bubbles escape the treated bath with less violence and with a corresponding reduction in the formation of mist particles. Foaming agents reduce mist formation by reducing bubble escape energy and by trapping the mist particles in a dense foam. The use of surfactants in chrome plating baths can reduce chromic acid losses by as much as 45 percent with a corresponding reduction in air and water pollution.

Foam, which has the disadvantage of trapping hydrogen gas, can create a fire hazard and must be continually replaced. Floating plastic objects such as polyethylene balls, hollow rods, and cylinders are also used.[75] The floating plastic used to cover the surface serves as a tank top and mist eliminator and reduces heat losses and ventilation requirements.

In one case the use of ¾-inch balls to cover 90 percent of the surface area of sulfuric acid solutions used in the electrorefining of copper resulted in a 90 percent reduction in evaporation losses and a 70 percent reduction in heat loss. The savings from the reduction in loss of methylated spirits (an addition agent) over a 2-week period paid for the balls. In addition to a 90 percent reduction in air pollution from sulfuric acid mist, there was a noticeable reduction in corrosion rates. The approximate cost of the ball cover is $1.50 to $2.00 per square foot of tank surface area. [75]

4.4.2.18 Liquid Distribution—Wet scrubbers require a uniform and consistent liquid distribution pattern for the maintenance of high scrubbing efficiencies at minimum water rates. Liquid distribution in wet scrubbers is accomplished by spray nozzles or spinning disk atomizers. Weir box or sieve plate distributors may be used for packed towers.

4.4.2.19 Spray Nozzles—Spray scrubbers require liquid droplets that are closely sized in order to avoid liquid entrainment at maximum gas flow rates. Since the scrubbing liquid is often recirculated, the spray nozzles must be capable of handling liquids with fairly high solids content.

The basic functions of liquid spray nozzles and atomizers are to create small droplets with large surface areas, to distribute the liquid in a specific pattern, to control liquid-flow metering, and to generate high-velocity droplets.[76-79] At least one of the above functions is involved in every industrial spraying process, and spray nozzle selection depends on the specific function to be performed. The spray devices used in wet scrubbers may be classified as pressure nozzles (hollow and solid cone and impingement and impact), rotating nozzles (spinning atomizers), and miscellaneous nozzles.

In hollow-cone spray nozzles, the fluid is fed to a whirl chamber—a tangential inlet (Figure 4-39a) or a fixed spiral (Figure 4-39b)—so that the fluid acquires rapid rotation. The orifice is on the axis of the chamber, and the fluid exits as a hollow conical sheet and then breaks up into droplets. The angle of the spray is determined by the dimensions of the swirl chamber and the pitch of the nozzle. A spiral with a short pitch produces a wide-angle spray; conversely, a long pitch produces a narrow-angle spray. The spray angle may range from 15 to 135 degrees.

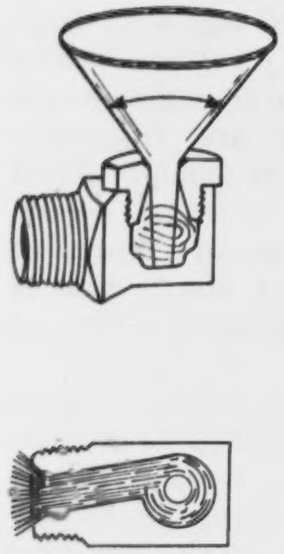
Hollow cone spray nozzles with cone angles of from 15 to 20 degrees (Figures 4-39b and 4-39c) are used in venturi jet scrubbers for maximum turbulence and mixing in the throat and diffuser section. Larger nozzle angles are used in air washers and humidifiers.

The solid cone nozzle (Figure 4-39d) is a modification of the hollow cone nozzle used when complete coverage of fixed area is desired. The nozzle is essentially a hollow-cone nozzle with the addition of a central axial jet. The jet strikes the outer rotating fluid inside the nozzle orifice and is broken into droplets. The angle of the spray is a function of nozzle design and is nearly independent of pressure. A second type of solid cone spray nozzle (Figure 4–39e) consists of an orifice and external helical spiral. The nozzle is essentially non-clogging and finds use in packed column distributor design. Commercial solid cone nozzles are available with included angles of from 30 to 100 degrees. Wet scrubbers nearly always use nozzles with large angle sprays. Solid-cone spray nozzles are frequently mounted in clusters (Figure 4-39f). Liquid distribution is enhanced by using several small sprays instead of one large spray of the same capacity. Liquid distribution is also improved by the proper selection of pipe manifold size.[78]

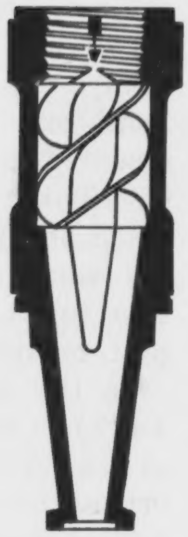
In the impingement-type nozzle (Figure 4-39g), a high-velocity liquid jet is directed at a solid target or a liquid stream. Proper orientation and shape of the target or control of the size and shape of the two fluid streams produces a hollow cone, fan, or dish-shaped spray pattern. The nozzles are robust and simple in shape, and despite higher cost, they are frequently used in wet scrubbing towers because of their more uniform distribution of droplet size.

Rotating nozzles (spinning atomizers) are a type of liquid distributor (Figure 4-39h) less frequently used in gas scrubbing than either hollow cone or solid cone nozzles. The droplets produced by rotating nozzles are uniform in size and can be controlled without regard to liquid feed rate by changing the disk speed. Spinning atomizers are used in some wet scrubbers and have the advantage of being able to handle slurries that could clog conventional nozzles. Among miscellaneous atomizers, the fan jet (Figure 4-39i) is used in wetting and light humidification operations.

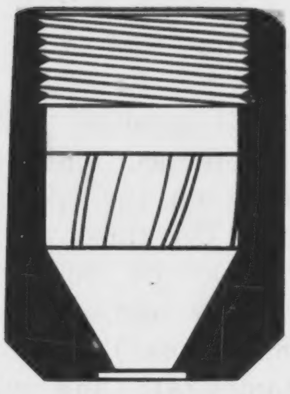
In packed tower and cross flow scrubber liquid distributor design, spray nozzles and drilled pipe headers may be used to distribute liquid. Most packed tower liquid distributors are of the weir box V-notch type (Figure 4-40a). For low rates of gas flow, weir risers (Figure 4-40b) may be used. Submerged orifice plate distributors (Figure 4-40c) are also used. Liquid distribution is critical in determining scrubber performance.[79]



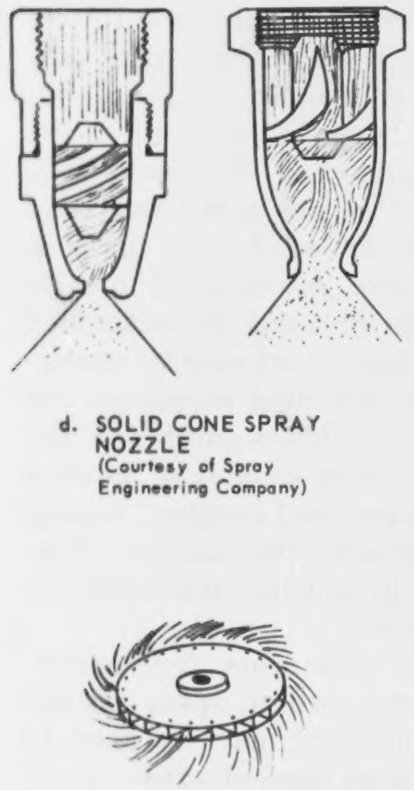
a. **HOLLOW CONE SPRAY NOZZLE**
(Courtesy of Spray Systems Company)



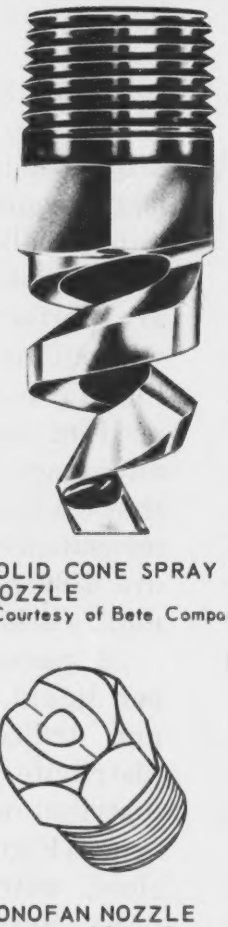
b. **HOLLOW CONE SPRAY NOZZLE**
(Courtesy of Schutte & Koerting)



c. **HOLLOW CONE SPRAY NOZZLE**
(Courtesy of Schutte & Koerting)

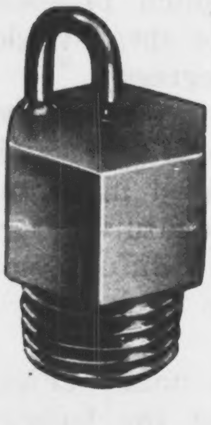


d. **SOLID CONE SPRAY NOZZLE**
(Courtesy of Spray Engineering Company)

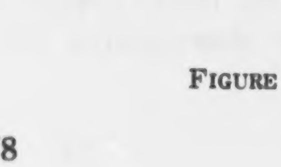


e. **SOLID CONE SPRAY NOZZLE**
(Courtesy of Bete Company)

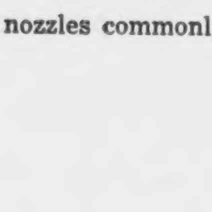
f. **CLUSTER SPRAY NOZZLE**
(Courtesy of Spray Engineering Company)



g. **PIN JET IMPINGEMENT SPRAY NOZZLE**
(Courtesy of Spray Engineering Company)

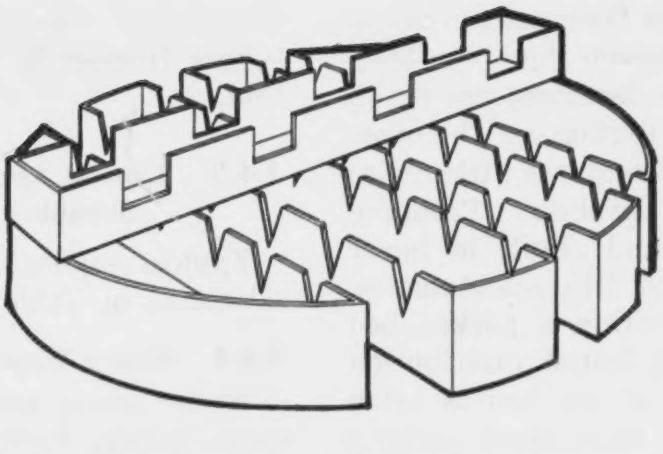


h. **SPINNING DISK SPRAY NOZZLE**
(Courtesy of Schutte & Koerting)

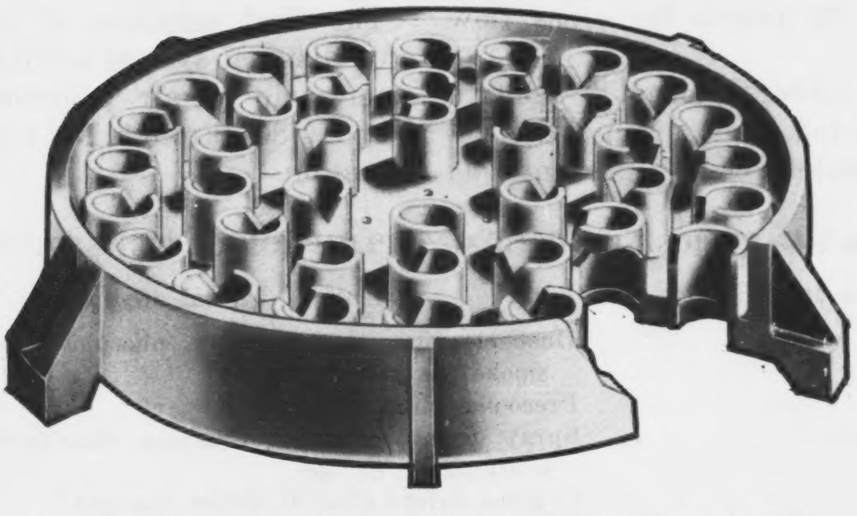


i. **MONOFAN NOZZLE**
(Courtesy of Spray Engineering Company)

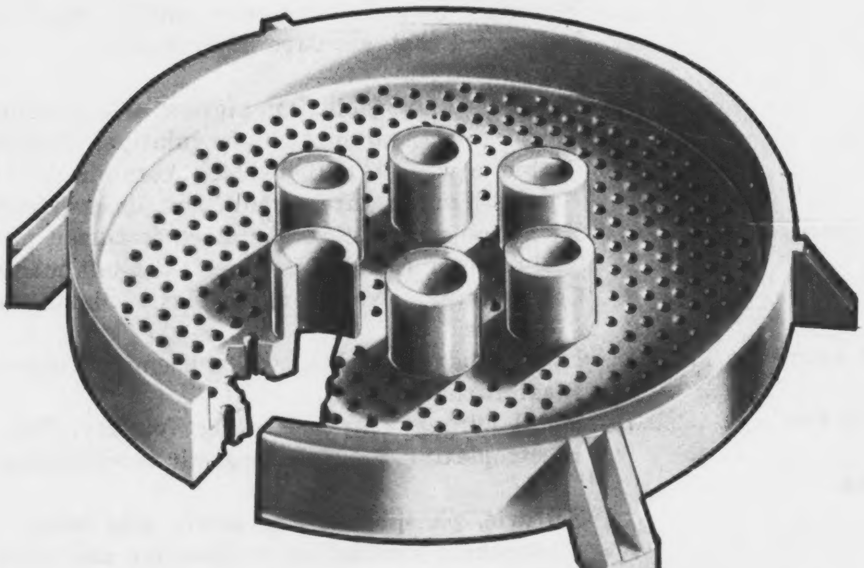
FIGURE 4–39. Spray nozzles commonly used in wet scrubbers.



a. PACKED TOWER WEIR BOX LIQUID DISTRIBUTOR
(Courtesy of Koch Engineering Company)



b. PACKED TOWER "WEIR RISER" LIQUID DISTRIBUTOR
(Courtesy of U. S. Stoneware Company)



c. "SUBMERGED ORIFICE" PLATE DISTRIBUTOR

FIGURE 4–40. Weir and sieve plate liquid distributors commonly used in packed towers. *(Courtesy of U.S. Stoneware Company)*

Because spray nozzles frequently wear or clog and produce an uneven liquid pattern, they require frequent replacement and maintenance. Weir box distribution, on the other hand, is dependable and requires little maintenance after initial leveling. Pumping heads are also lower and result in lower power requirements and less maintenance.

Liquid distribution within a packed bed is also very important. Initial distribution of liquid onto the top of the bed is often enhanced by the use of small sized packing in the top of the bed.

Normal drip point requirements for weir box distribution range from 8 to 10 points per square foot for vertical packed beds and from 15 to 30 points for cross flow scrubbers.

Cross flow scrubbers normally contain baffles or corrugated walls around the periphery of the packed bed to prevent gas channeling. Packed beds above 15 feet in height frequently require liquid redistribution.

4.4.3 Typical Applications of Wet Scrubbers

Typical applications of wet scrubbers are tabulated in Table 4-6.

4.4.4 Water Disposal

Water usage and waste disposal may become critical factors in the final selection of a wet scrubber. Waste quantity, particle size distribution in the slurry, recovery value, corrosiveness of the solutions, and materials of construction are important factors. The final selection of a water treatment or disposal system should not result in water, soil, or air pollution. Refer to references 80 through 92 for additional information.

Table 4-6.—TYPICAL INDUSTRIAL APPLICATION OF WET SCRUBBERS

Scrubber type	Typical application
Spray chambers	Dust cleaning, electroplating, phosphate fertilizer, kraft paper, smoke abatement
Spray tower	Precooler, blast furnace gas
Centrifugal	Spray dryers, calciners, crushers, classifiers, fluid bed processes, kraft paper, fly ash
Impingement plate	Cupolas, driers, kilns, fertilizer, flue gas
Venturi:	
Venturi throat	Pulverized coal, abrasives, rotary kilns, foundries, flue gas, cupola gas, fertilizers, lime kilns, roasting, titanium dioxide processing, odor control, oxygen steel making, coke oven gas, fly ash
Flooded disk	
Multiple jet	
Venturi jet	Fertilizer manufacture, odor control, smoke control
Vertical venturi	Pulverized coal, abrasive manufacture
Packed bed:	
Fixed	Fertilizer manufacturing, plating, acid pickling
Flooded	Acid vapors, aluminum inoculation, foundries, asphalt plants, atomic wastes, carbon black, ceramic frit, chlorine tail gas, pigment manufacture, cupola gas, driers, ferrite, fertilizer
Fluid (floating) ball	Kraft paper, basic oxygen steel, fertilizer, aluminum ore reduction, aluminum foundries, fly ash, asphalt manufacturing
Self-induced spray	Coal mining, ore mining, explosive dusts, air conditioning, incinerators
Mechanically-induced spray	Iron foundry, cupolas, smoke, chemical fume control, paint spray
Disintegrator	Blast furnace gas
Centrifugal fan Inline fan	Metal mining, coal processing, foundry, food, pharmaceuticals
Wetted filters	Electroplating, acid pickling, air conditioning, light dust
Dust, mist eliminators:	
Fiber filters	Sulfuric, phosphoric, and nitric acid mists; moisture separators; household ventilation; radioactive and toxic dusts, oil mists
Wire mesh	Sulfuric, phosphoric, and nitric acid mists; distillation and absorption
Baffles	Coke quenching, kraft paper manufacture, plating
Packed beds	Sulfuric and phosphoric acid manufacture, electroplating spray towers

4.4.4.1 Settling Tanks and Ponds—This method of disposal may be applied to scrubber discharges containing solid particulate matter that readily settles or is easily flocculated by chemical treatment. Tank or pond size may be easily determined by laboratory sedimentation tests.[80] Separation by sedimentation is usually limited to particles larger than 1 micron or to particles that readily flocculate. Advantages are that waste products to be disposed of may be sluiced to a burial pit, waste water may be chemically treated and reused, operational costs are low, and abrasive solids can be handled. Disadvantages are that a large area is required for the settling of small particles, ground water contamination from ponds is possible, and natural evaporation to the atmosphere occurs.

4.4.4.2 Continuous Filtration—This method of slurry treatment is usually applied where the solids have some recovery value or are porous or incompressible.[81] Advantages are a dewatered waste product and moderate space requirements. Disadvantages are high initial cost and relatively high maintenance and operational costs.

4.4.4.3 Liquid Cyclones—The wet cyclone has come into prominence in the last few years as a method for concentrating solids. The advantages are low initial cost, low maintenance, ability to handle abrasive solids, and low space requirements. Disadvantages are the production of high solids filtrate or overflow and relatively high power requirements. [82]

4.4.4.4 Continuous Centrifuge—This method of solids separation can sometimes be applied to submicron slurries at fairly high collection efficiencies.[83] The advantages are low space requirements and a large variety of designs for special requirements. Disadvantages are high capital and operating costs and susceptibility to abrasion and corrosion.

4.4.4.5 Chemical Treatment—Chemical treatment of liquid wastes includes treatment with chlorine, lime, soda ash, carbon dioxide, ammonia, corrosion inhibitors, coagulants, and/or limestone soak pits.[84–93]

4.5 HIGH-VOLTAGE ELECTROSTATIC PRECIPITATORS

4.5.1 Introduction

The high-voltage electrostatic precipitator (ESP) is used at more large installations than any other type of high-efficiency particulate matter collector. For many operations, such as coal-fired utility boilers, the high-voltage electrostatic precipitator is the only proven high-efficiency control device available today. High-voltage single-stage precipitators have been used successfully to collect both solid and liquid particulate matter from smelters, steel furnaces, petroleum refineries, cement kilns, acid plants, and many other operations. Figures 4-41 and 4-42 show typical electrostatic precipitator installations.

Electrostatic precipitators are normally used when the larger portion of the particulate matter to be collected is smaller than 20 microns in mean diameter. When particles are large, centrifugal collectors are sometimes employed as precleaners. Gas volumes handled normally range from 50,000 to 2,000,000 cubic feet per minute. Operating pressures range from slightly below atmospheric pressure to 150 pounds per square inch gauge and operating temperatures normally range from ambient air temperatures to 750° F.

4.5.2 Operating Principles

Separation of suspended particulate matter from a gas stream by high-voltage electrostatic precipitation requires three basic steps:

1. Electrical charging of the suspended matter.
2. Collection of the charged particulate matter on a grounded surface.
3. Removal of the particulate matter to an external receptacle.

A charge may be imparted to particulate matter prior to the electrostatic precipitator by flame ionization or friction; however, the bulk of the charge is applied by passing the suspended particles through a high-voltage, direct-current corona.[94] The corona is established between an electrode maintained at high voltage and a grounded collecting

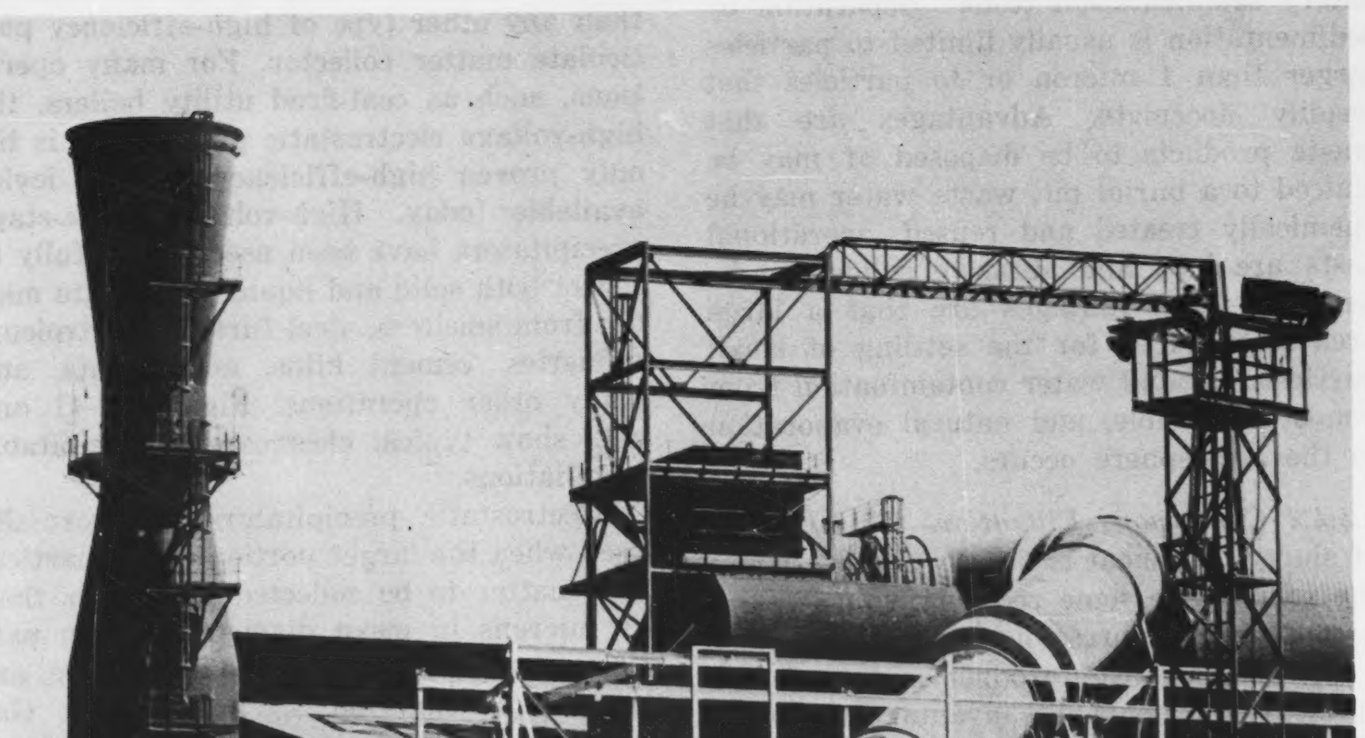


FIGURE 4–41. **Multiple precipitator installation in basic oxygen furnace plant.**

(Courtesy of Koppers Co. Inc.)

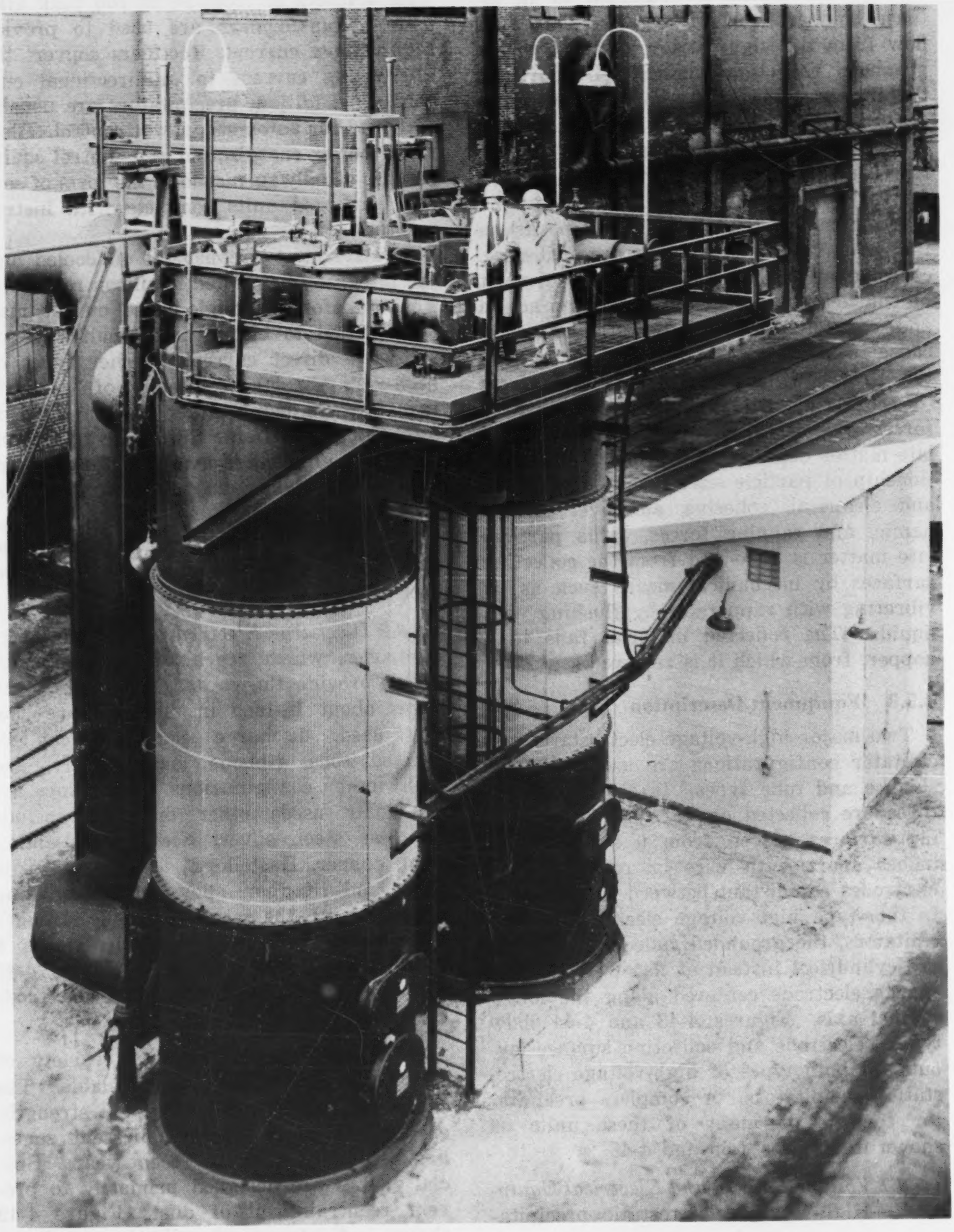


FIGURE 4–42. Detarrer precipitators installed in steel mill.

(Courtesy of Koppers Co. Inc.)

surface.* Particulate matter passing through the corona is subjected to an intense bombardment of negative ions that flow from the high-voltage electrode to the grounded collecting surface. The particles thereby become highly charged within a fraction of a second and migrate toward the grounded collecting surfaces. This attraction is opposed by inertial and friction forces.

After the particulate matter deposits on the grounded collecting surface, adhesive, cohesive, and primary electrical forces must be sufficient to resist any gas stream action and counter electrical forces that would cause reentrainment of the particulate matter. Free flowing liquids are removed from the collecting surface by natural gravity forces. Successful removal of other particulate matter depends on a complex interrelationship of particle size, density, and shape and electrical, cohesive, adhesive, aerodynamic, and rapping forces. This particulate matter is dislodged from the collecting surfaces by mechanical means such as by vibrating with rappers or by flushing with liquids. The collected material falls to a hopper, from which it is removed.

4.5.3 Equipment Description

Two major high-voltage electrostatic precipitator configurations are used: the flat surface and tube types. In the first, particles are collected on flat, parallel collecting surfaces spaced from 6 inches to 12 inches apart with wire or rod discharge electrodes equidistant between the surfaces. In tube-type high-voltage electrostatic precipitators, the grounded collecting surfaces are cylindrical instead of flat with the discharge electrode centered along the longitudinal axis. Figures 4-43 and 4-44 show typical electrode and collecting surface layouts for both types of high-voltage electrostatic precipitators. A complete precipitator consists of many of these units as shown in Figures 4-45 and 4-46.

4.5.3.1 Voltage Control and Electrical Equipment—High-voltage electrostatic precipitators operate with unidirectional current and with voltages of from 30 to 100 peak kilovolts. Transformers are used to provide high-voltage current. Rectifiers convert the alternating current to unidirectional current. In addition, precipitators are usually equipped for automatic power control. Electrical power energization and control equipment is usually furnished in the form of several packaged units complete with instrumentation.

Transformers are usually oil cooled and are integrally connected to silicon rectifiers. The transformer single-phase output may be rectified to either double-half-wave or full-wave direct current. Earlier types of high-voltage sets consisted of separate transformers using either vacuum tube or mechanical rectifiers. Silicon rectifier conversion equipment is available for modernizing existing vacuum tube or mechanical rectifiers.

Figure 4-47 shows one type of transformer-rectifier unit, and Figure 4-48 shows one type of power control unit.

4.5.3.2 Discharge Electrodes—The discharge electrodes, which are almost always energized, provide the corona. Although round wires about $1/8$-inch in diameter are usually used, discharge electrodes can be twisted rods, ribbons, barbed wire, and many other configurations. Steel alloys are commonly used; other materials include stainless steel, silver, Nichrome®, aluminum, copper, Hastelloy®, lead-covered iron wire, and titanium alloy. Any conducting material with the requisite tensile strength that is of the proper configuration is a feasible discharge electrode. Figure 4-49 shows some common discharge electrode configurations.

4.5.3.3 Collecting Surfaces—A variety of flat collecting surfaces is available. The use of smooth plates, with fins to strengthen them and to produce quiescent zones, has become common in recent years. Special shapes are designed primarily to prevent reentrainment of dust. Figure 4-49 shows some types of collecting surfaces. Essentially all tubular collecting surfaces are standard pipe.

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*The terms "collecting electrode" and "grounded collecting surface" are often used synonymously.

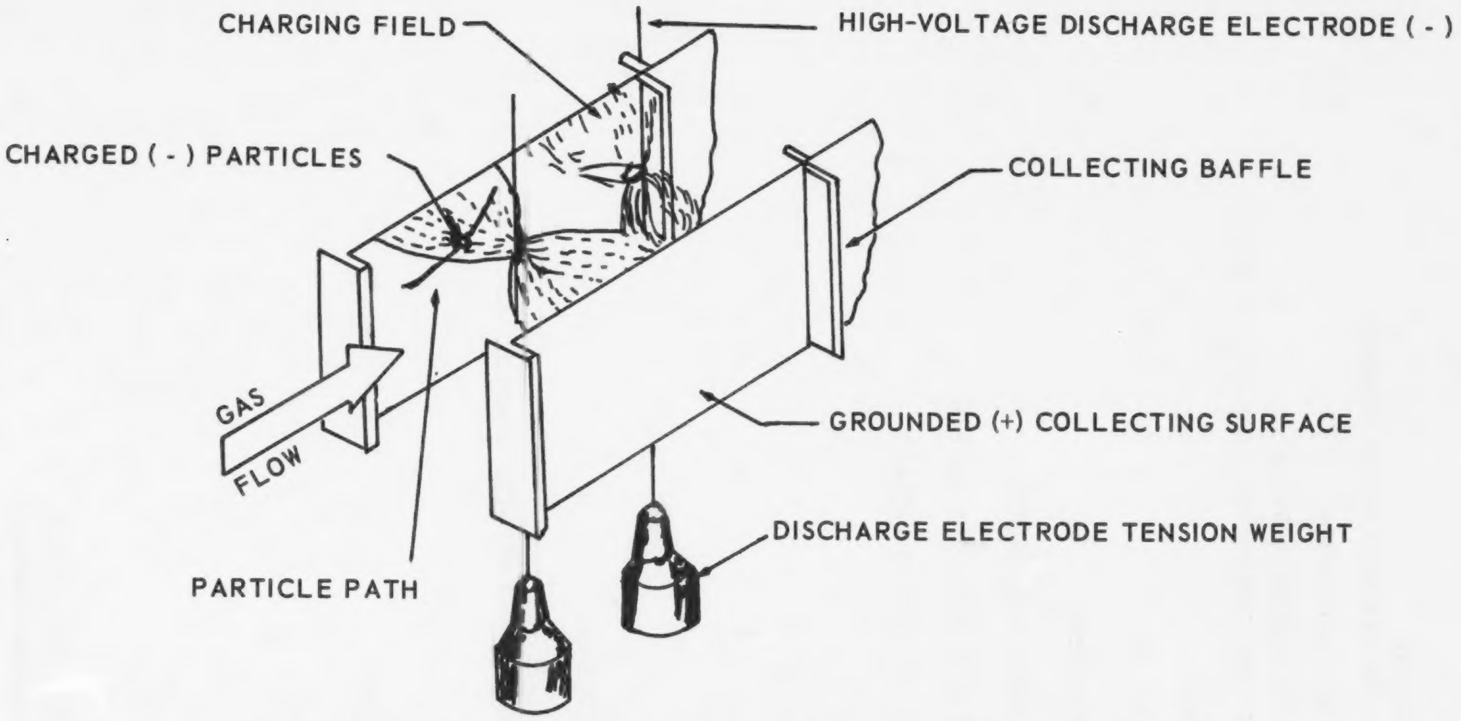

CHARGING FIELD
HIGH-VOLTAGE DISCHARGE ELECTRODE (-)
CHARGED (-) PARTICLES
COLLECTING BAFFLE
GAS FLOW
GROUNDED (+) COLLECTING SURFACE
DISCHARGE ELECTRODE TENSION WEIGHT
PARTICLE PATH

FIGURE 4-43. Schematic view of a flat surface-type electrostatic precipitator.

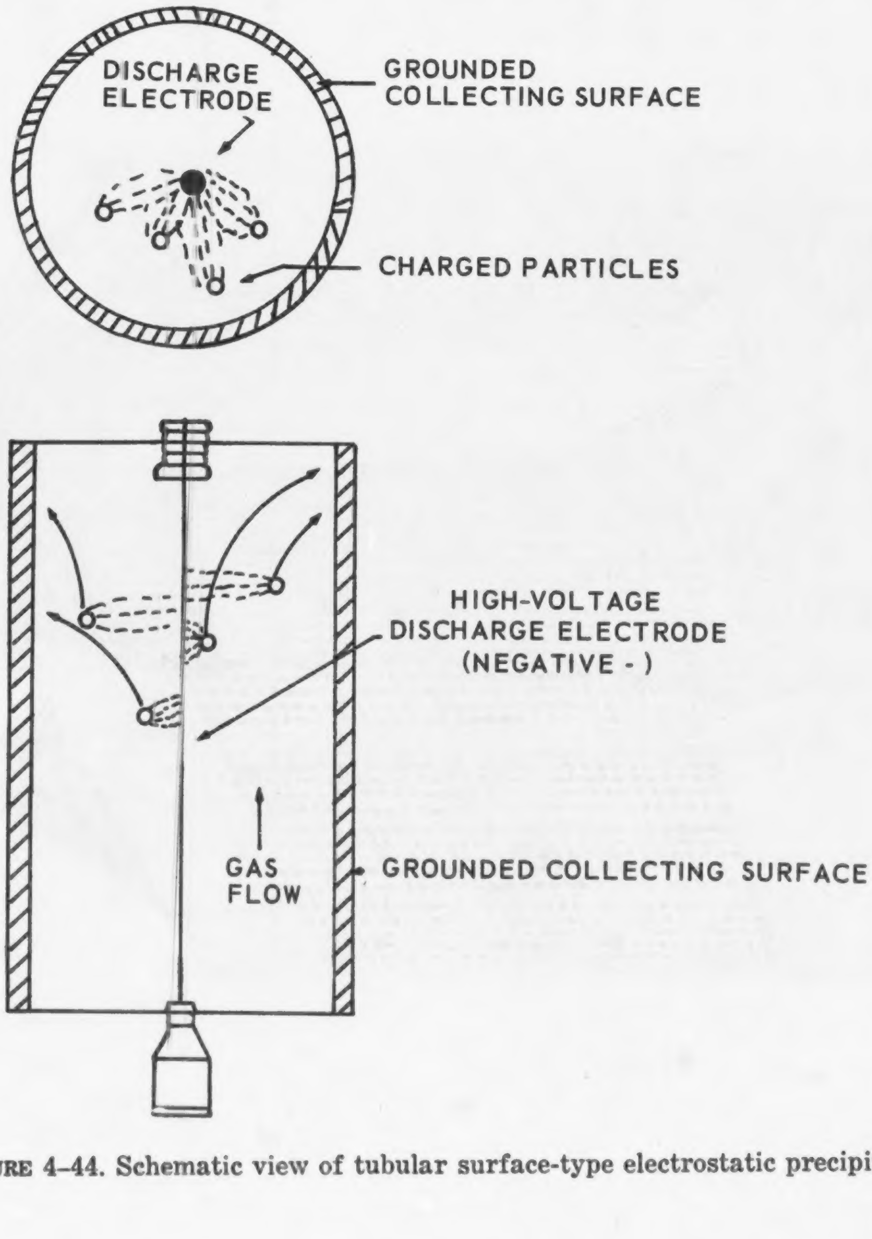

DISCHARGE ELECTRODE
GROUNDED COLLECTING SURFACE
CHARGED PARTICLES
HIGH-VOLTAGE DISCHARGE ELECTRODE (NEGATIVE -)
GAS FLOW
GROUNDED COLLECTING SURFACE

FIGURE 4-44. Schematic view of tubular surface-type electrostatic precipitator.

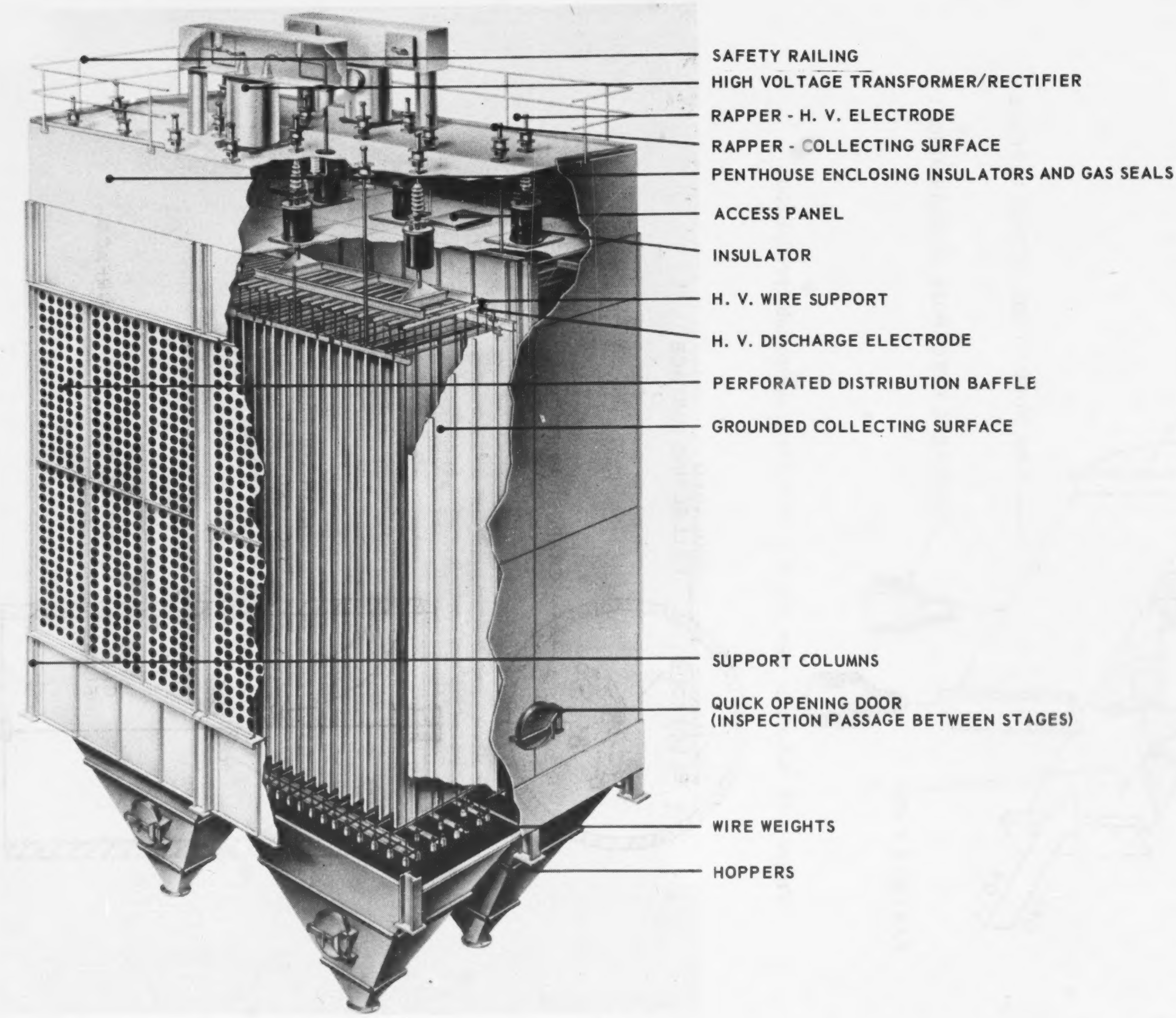

SAFETY RAILING
HIGH VOLTAGE TRANSFORMER/RECTIFIER
RAPPER - H. V. ELECTRODE
RAPPER - COLLECTING SURFACE
PENTHOUSE ENCLOSING INSULATORS AND GAS SEALS
ACCESS PANEL
INSULATOR
H. V. WIRE SUPPORT
H. V. DISCHARGE ELECTRODE
PERFORATED DISTRIBUTION BAFFLE
GROUNDED COLLECTING SURFACE
SUPPORT COLUMNS
QUICK OPENING DOOR
(INSPECTION PASSAGE BETWEEN STAGES)
WIRE WEIGHTS
HOPPERS

Figure 4–45. Cutaway view of a flat surface-type electrostatic precipitator.
(Courtesy of UOP Air Correction Division)

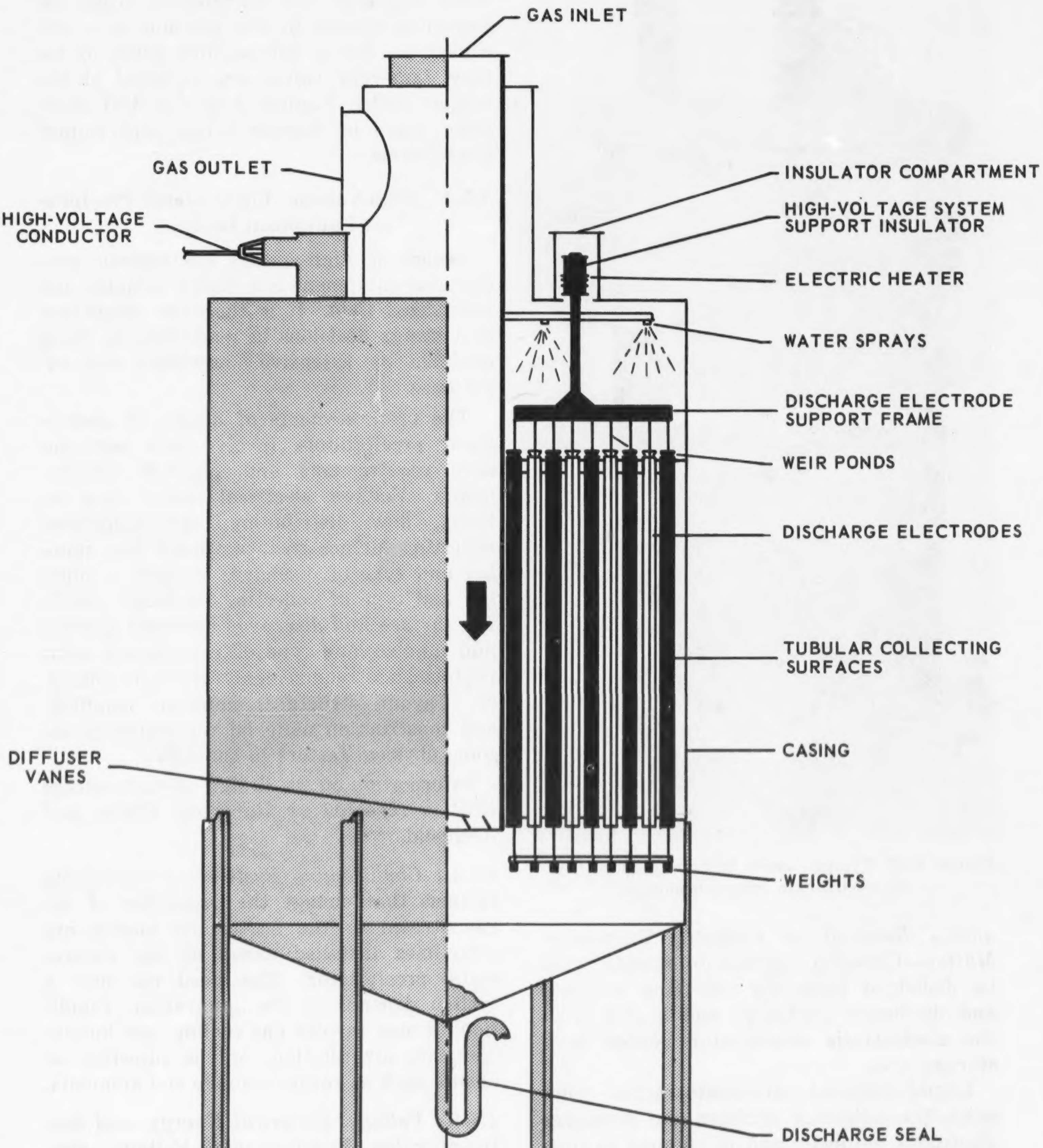

GAS INLET
GAS OUTLET
HIGH-VOLTAGE CONDUCTOR
INSULATOR COMPARTMENT
HIGH-VOLTAGE SYSTEM SUPPORT INSULATOR
ELECTRIC HEATER
WATER SPRAYS
DISCHARGE ELECTRODE SUPPORT FRAME
WEIR PONDS
DISCHARGE ELECTRODES
TUBULAR COLLECTING SURFACES
CASING
DIFFUSER VANES
WEIGHTS
DISCHARGE SEAL

FIGURE 4–46. Cross-sectional view of irrigated tubular blast furnace precipitator.
(Courtesy of Koppers Co. Inc.)

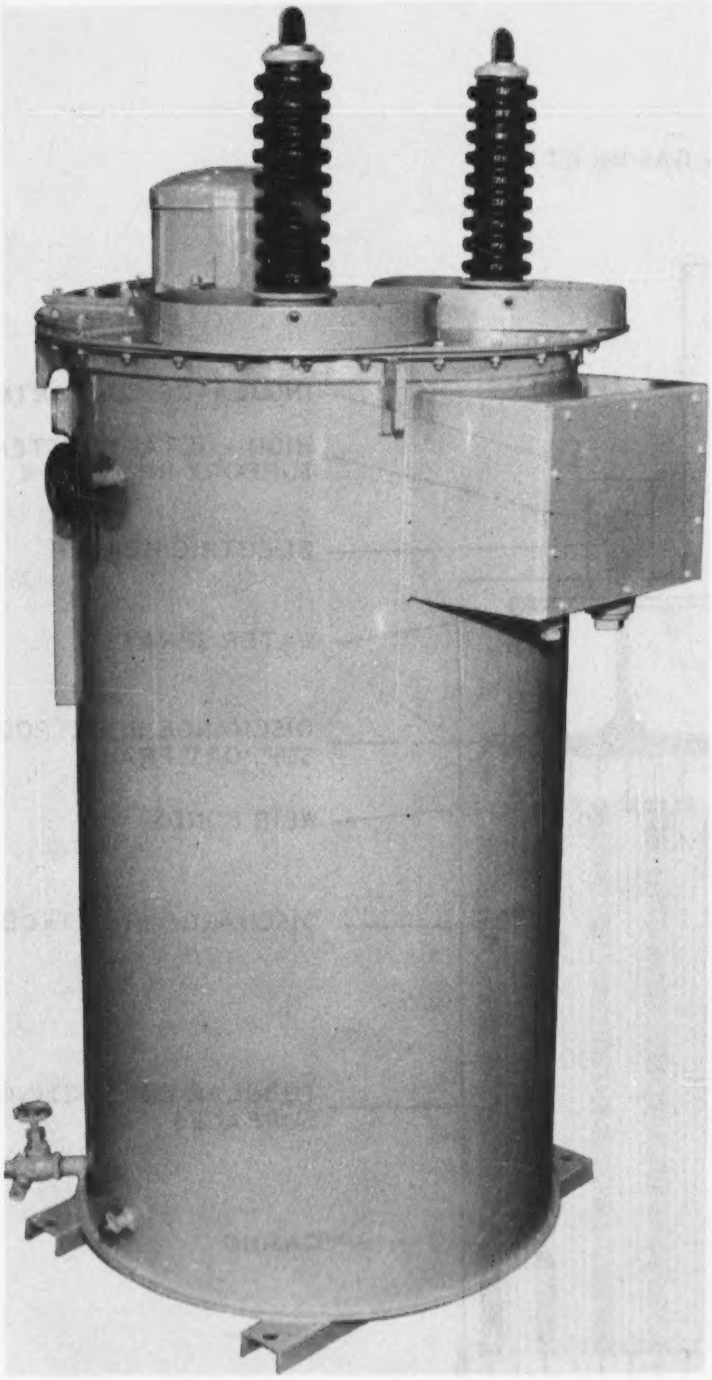


FIGURE 4–47. Typical double half wave silicone rectifier with twin output bushings.

4.5.3.4 Removal of Collected Particulate Matter—Collected particulate matter must be dislodged from the collecting surfaces and discharge electrodes and moved from the electrostatic precipitator hopper to a storage area.

Liquid collected particulate matter flows down the collecting surfaces and discharge electrodes naturally and is pumped to storage.

Solid collected particulate matter is usually dislodged from collecting surfaces by pneumatic or electromagnetic vibrators or rappers. At times, motor driven hammers are used for this purpose or sprays are used to flush materials from collecting surfaces. Solid materials are transferred from the hopper to storage by air, vacuum, or screw conveyors. Swing valves, slide gates, or rotary vane-type valves are installed at the hopper outlet. Figures 4-50 and 4-51 show some types of hopper valves and rapper mechanisms.

4.5.4 High-Voltage Electrostatic Precipitator Equipment Design

Design of high-voltage electrostatic precipitator equipment is a highly complex and specialized field. It is therefore important that design decisions be made only by those qualified by extensive knowledge and experience.

The basic elements of design of electrostatic precipitators involve both performance requirements and physical requirements. Voltage, electrical energy, gas velocity, flow distribution, sectionalization, collecting surface area, treatment time, number and type of discharge electrodes, number and type of collecting surfaces, collecting surface and discharge electrode spacing and number and type of rappers are some performance requirement factors to consider. Layout, structure, materials handling, and construction material requirements are some physical factors to consider.

Information on the design of high-voltage ESP is reported by Ramsdell, White, and Archbold.[94-96]

4.5.4.1 Conditioning Systems—Conditioning systems that change the properties of the gas stream or the particulate matter are sometimes installed ahead of the electrostatic precipitator. The need for such a system depends on the application. Conditioning may involve gas cooling, gas humidification, air dilution, or the injection of agents such as sulfur trioxide and ammonia.

4.5.4.2 Voltage, Electrical Energy, and Sectionalization Requirements—Voltage, electrical energy, and sectionalization are interrelated. The design of the high-voltage electrostatic precipitator should provide for a peak voltage sufficient for consistent op-

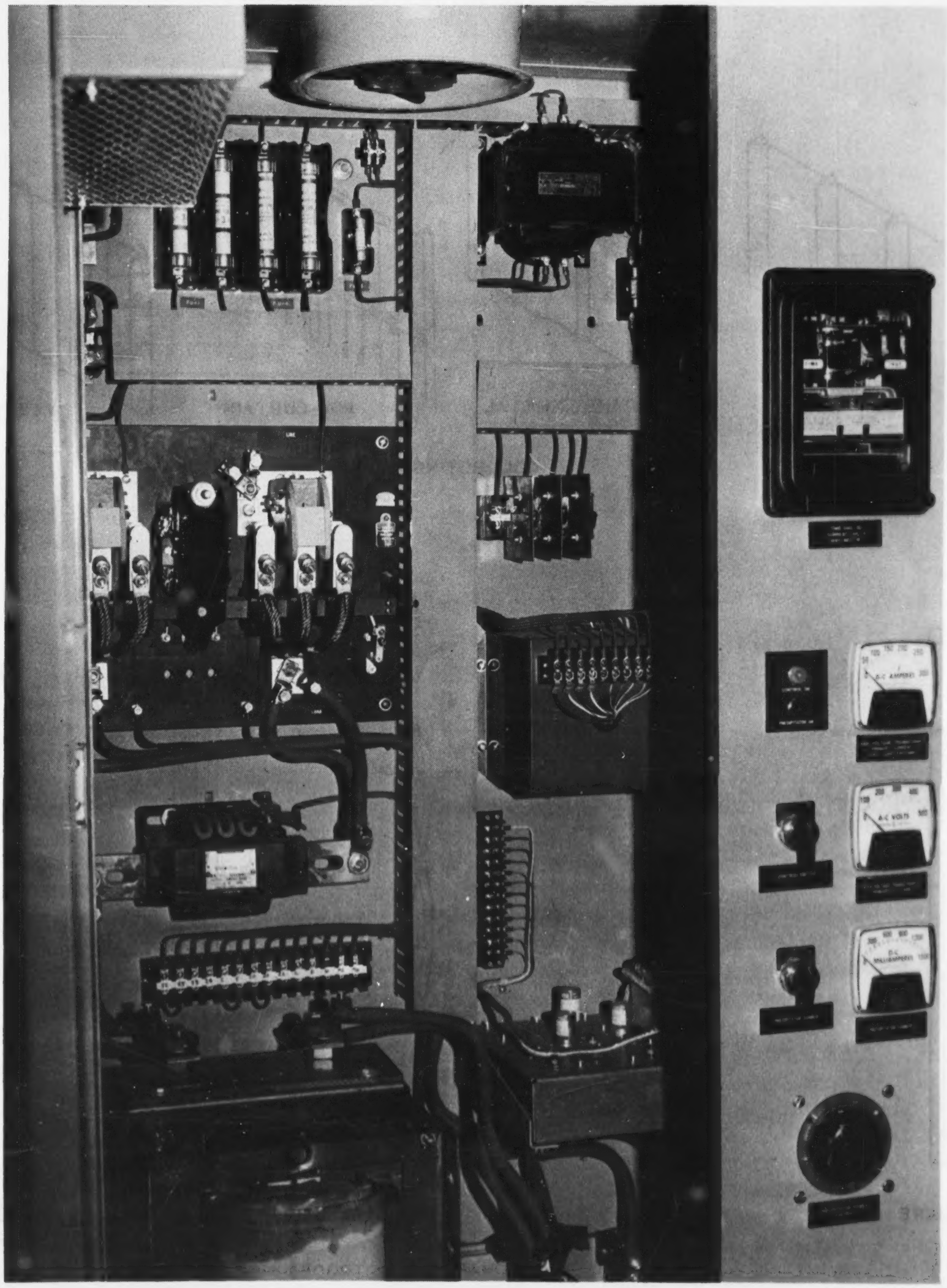
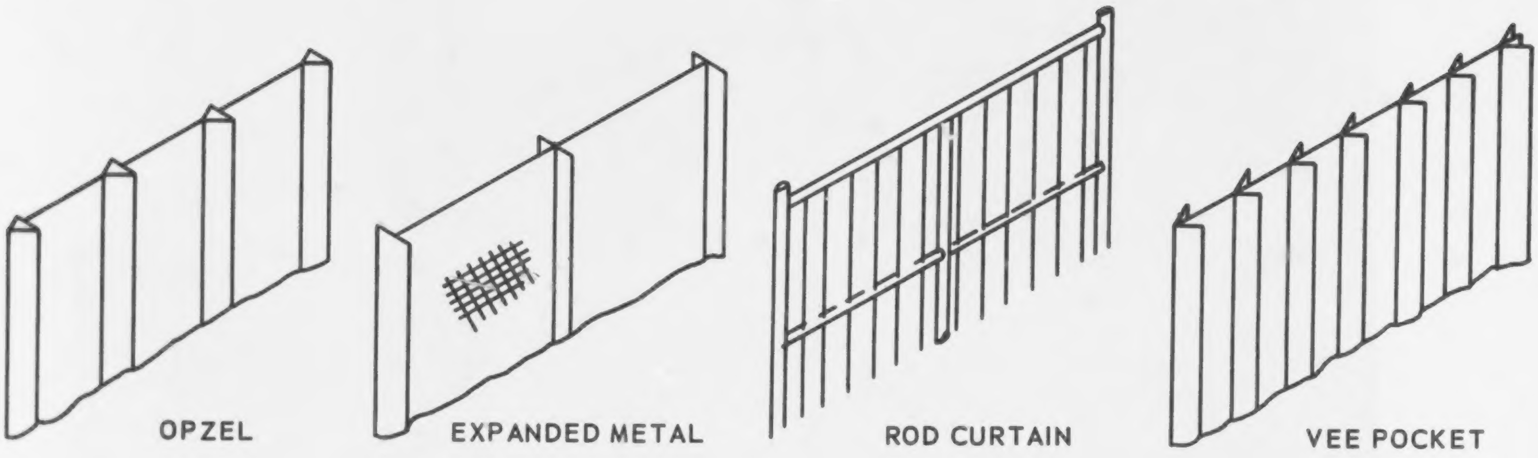
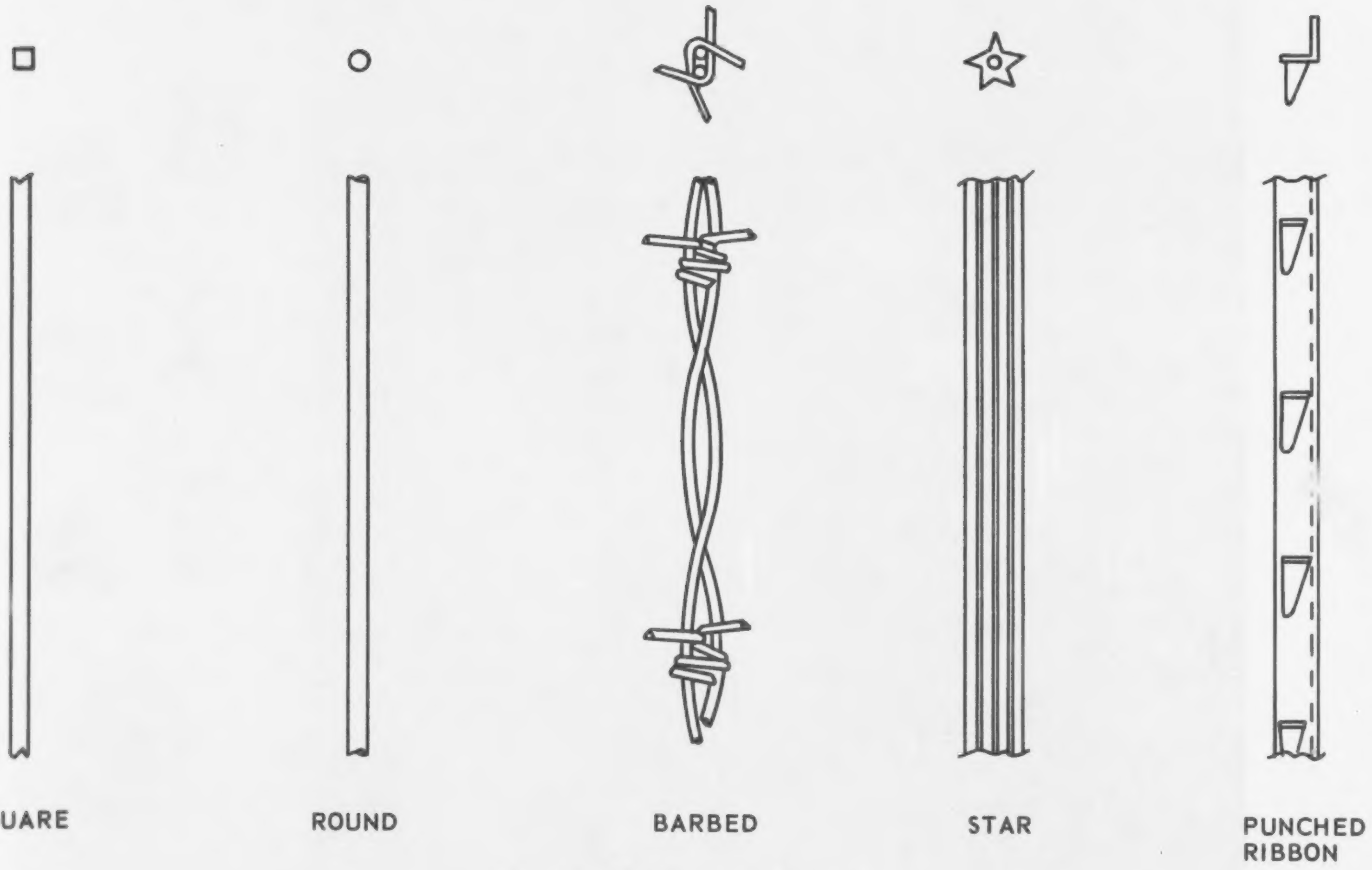

A-C AMPERES
A-C VOLTS
D-C MILLIAMPERES

FIGURE 4–48. Internal view of one type of rectifier control console showing component parts.
(Courtesy of Koppers Co. Inc.)


OPZEL
EXPANDED METAL
ROD CURTAIN
VEE POCKET

a. COLLECTING PLATES


SQUARE
ROUND
BARBED
STAR
PUNCHED RIBBON

b. DISCHARGE ELECTRODES

FIGURE 4-49. Electrostatic precipitator collecting plates and discharge electrodes.

eration of the unit within required performance limits. The design should also provide for automatic power control and sufficient electrical power to handle all load conditions. When necessary, the design should provide for sectionalization so that voltage may be adjusted to compensate for different conditions in different sections of the electrostatic precipitator.

The peak voltage requirements of a high-voltage electrostatic precipitator depend on the application and design, and usually range from 30 to 100 kilovolts. Peak voltage requirements depend largely on the spacing of electrodes and collecting surfaces. The composition, pressure, and temperature of the gas stream and the concentration of particulate matter in the gas stream also influence peak voltage design requirements.

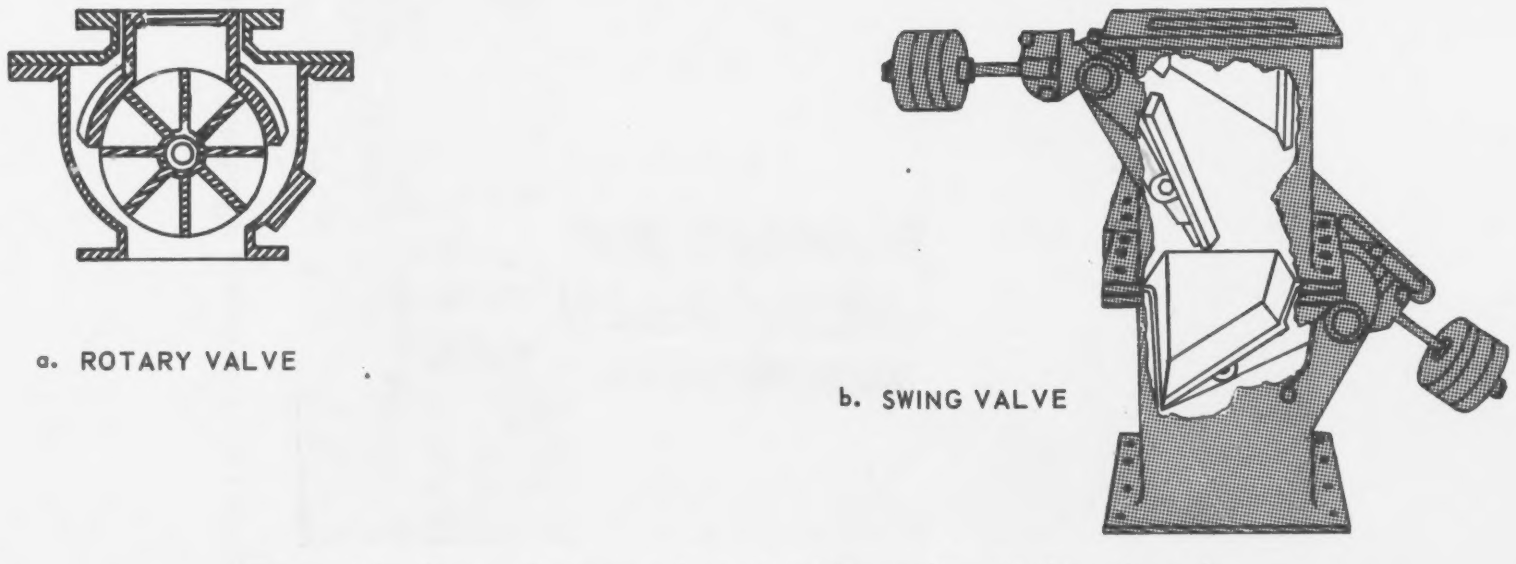
For continuous high-efficiency performance, sectionalization usually is required. The power supply and controls for each precipitator section are energized separately to prevent power fluctuations from spreading from section to section. The power controls regulate current, voltage, and sparking. The number of sections required depends on performance requirements and the application. For some applications sparking is not desirable. Where sparking is desirable, there is often an optimum spark rate that will give the best performance. An example of this effect is shown in Figure 4-52.[97]

4.5.4.3 Gas Velocity, Treatment Time, and Flow Distribution—Gas velocities range from 3 to 15 feet per second. Low linear gas velocities promote deposition and help minimize re-entrainment of particulate matter. The cross-sectional area of the electrostatic precipitator determines the linear gas velocity for a given gas volume. Longer treatment time promotes more effective deposition of particulate matter. The length of the treatment section of the electrostatic precipitator determines the treatment time for a given linear gas velocity.

Uniform flow distribution is an important design factor. Perforated plates are installed at the inlet and sometimes at the outlet of the electrostatic precipitator, and vanes are often installed in the inlet and outlet ductwork to distribute the flow of the gas stream. When it is necessary to install bends or elbows near the inlet or outlet, turning vanes are helpful. Experimental gas flow models are most useful as an aid to flow distributor design.

4.5.4.4 Collecting Surfaces and Discharge Electrodes—The number, type, size, and spacing of collecting surfaces and discharge electrodes required is dependent on the application and desired performance. For a given application, an increase in the total collecting surface area will usually improve performance provided adequate corona power is supplied.

4.5.4.5 Materials of Construction—Choice of materials for shells, collecting surfaces, elec-



a. ROTARY VALVE

b. SWING VALVE

FIGURE 4-50. Hopper discharge valves. (a) Rotary valve and (b) swing valve.

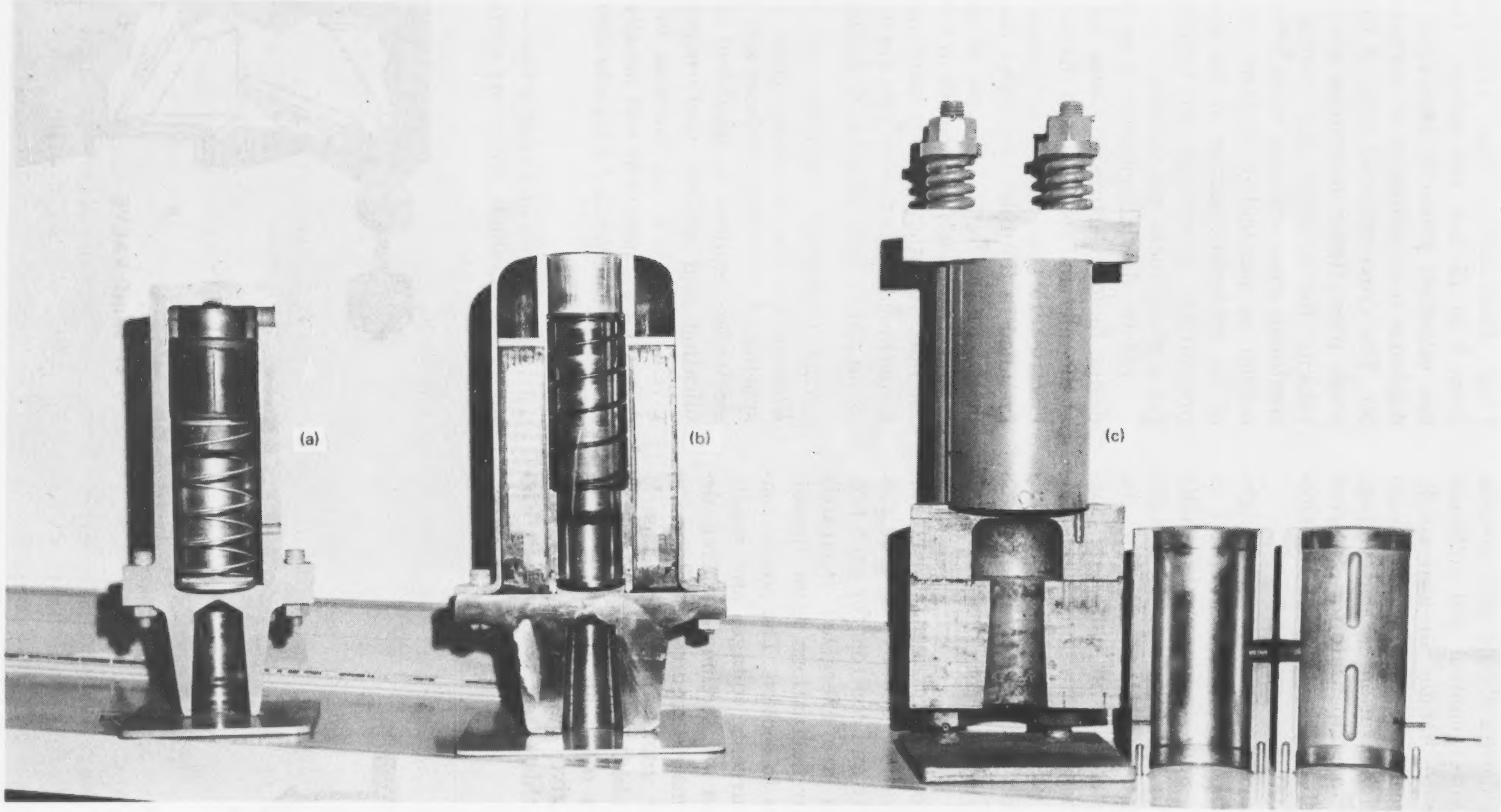


FIGURE 4–51. Electrostatic precipitator rapper mechanisms. (a) Pneumatic impulse rapper. (b) Magnetic impulse rapper, and (c) pneumatic reciprocating rapper.

(Courtesy of Koppers Co. Inc.)

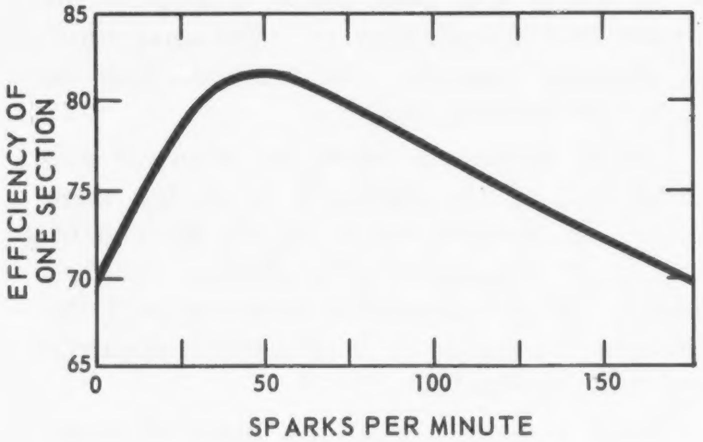


FIGURE 4-52. Variation of precipitator efficiency with sparking rate for a given fly-ash precipitator.

trodes, hoppers, and other surfaces is governed by cost and serviceability. Corrosion and temperature resistance are the two most important factors to consider. Steel construction is used wherever possible; however, aluminum, lead, concrete, wood, ceramics, plastics, plastic coated metals, and many other materials can be employed.

4.5.4.6 Collected Particulate Matter Handling Systems—Electrostatic precipitator hopper walls should be sloped to promote free flow of collected material. When materials stick or bridge in the hopper, vibrators or rappers should be attached to the outside of the hopper walls at strategic locations.

Hopper outlet valves should be designed to operate freely under all conditions. The hopper discharge system should also be designed to minimize gas leakage into or out of the electrostatic precipitator to prevent re-entrainment of the collected particulate matter.

4.5.4.7 Controls and Instruments—Useful controls and instruments are:

1. Individual electrical set controls and indicators.
2. Spark rate indicators.
3. Rapping cycle, frequency, intensity, and duration controls and indicators.
4. Outlet opacity indicator.
5. Line voltage indicators.

Recorders are useful for providing a permanent record of performance. Alarms are used to signal when control variables deviate from normal and when control valves, gates, or conveyors fail to function properly.

4.5.4.8 Layout—An electrostatic precipitator system should be designed to conserve space and to minimize costs. Other factors to consider are provision for future additions of equipment and the effect of the layout on gas flow distribution.

4.5.5 Specifications and Guarantees

Little published information is available on design criteria for electrostatic precipitators. It is therefore advisable for persons without extensive knowledge of and experience with the application of electrostatic precipitators to rely on several different vendors or consultants to furnish specifications. Forms used by members of the Industrial Gas Cleaning Institute are helpful for reporting and tabulating necessary information. These forms specify the information that the vendor needs to make a comprehensive proposal. This form includes information on:

1. The purchasing company.
2. The proposal.
3. The application.
4. Operating and design conditions.
5. Properties of the particulate matter and the gas stream.
6. Inlet particulate matter loadings.
7. Desired outlet loadings.
8. Desired efficiency.

When the purchaser lacks sufficient information to complete the form, the vendor can often draw on his knowledge and experience to supply the missing information or can advise the purchaser on further action. The purchaser may also retain consultants for guidance.

Industrial Gas Cleaning Institute publication No. EP-4 is useful for bid evaluation. Major sections of this form relate to:

1. Operating and performance data.
2. Precipitator arrangement.
3. Collecting system.
4. Electrical systems.
5. Other auxiliary equipment and services.

The purchaser should select specifications from the information submitted by the several vendors. Any differences in equipment or services proposals should be reconciled by consultation with the vendors or other experts. The specifications selected should be used to solicit final bids.

The purchase agreement should include a performance guarantee (when desirable), conditions for measuring performance, and specifications. Information that may be used for guidance in the preparation of purchase agreements is published by the Industrial Gas Cleaning Institute.[98-100]

4.5.6 Maintaining Collection Efficiency

A well designed precipitator properly maintained and operated within design limits will perform consistently at or above design efficiencies throughout its serviceable life.

Loss of efficiency is commonly caused by overloading, process changes, or inadequate maintenance. Increasing output or process gas flows without adding precipitator sections usually reduces electrostatic precipitator efficiency. Changes in raw materials, products, fuels, and gas stream conditions can also lead to poor performance. If these factors are anticipated in the original design, loss of efficiency can often be avoided.

It is not always possible to anticipate changes in the properties of particulate matter and the gas stream. It is therefore important that collector performance be monitored frequently by sampling the outlet gas stream. When inspection and maintenance fail to bring performance to within design limits and overloading is not a factor, the cause of poor performance is usually traceable to changes in properties of the particulate matter or the gas stream. Should this occur, consultation with the manufacturer of the equipment or with other experts is in order.

4.5.7 Improvement of Collection Efficiency

Process changes or changes in air pollution control requirements may make it necessary to improve the efficiency of an electrostatic preciptator. When no provision has been made for future additions, it may be less costly to scrap the older unit and to install a modern, more efficient unit. If provision has been made originally for layout and installation of additional units to increase capacity, the changes may be made at nominal cost.

Before action is taken to improve efficiency, all of the elements of design mentioned in Section 4.5.4 should be considered and compared with process requirements. The modifications required will depend on the degree of improvement required and the application.

When process conditions have changed, changing the voltage or power supply of the unit may improve the performance. Increasing the number of high-tension bus sections may at times improve performance. The installation of automatic power controls alone seldom results in significant improvement; however, use of this technique in conjunction with other techniques such as increased sectionalization is often effective.

Installing additional high-voltage electrostatic precipitator sections is the most common technique for improving collection efficiency. At times efficiency may be improved sufficiently by distributing the flow more uniformly within the unit or in the ductwork leading to the unit. In exceptional cases, modification of material handling systems may bring about the necessary improvement.

Changing the temperature of the gas stream or injecting other materials into the gas stream may improve efficiency.[101, 102] Whenever foreign materials are injected the air pollution aspects of these materials should be considered.

4.5.8 Typical Applications

High-voltage electrostatic precipitators have been used successfully to collect a wide variety of solid and liquid particles. Various applications for high-voltage electrostatic precipitators are included in Table 4-2.

4.5.8.1 Pulverized Coal-Fired Power Plants—The arrangement in Figure 4–53 depicts a pulverized coal unit. Typical of older systems, the mechanical precleaner (multiple cyclone) and the electrostatic precipitator are located downstream of the air heater. Gases range in

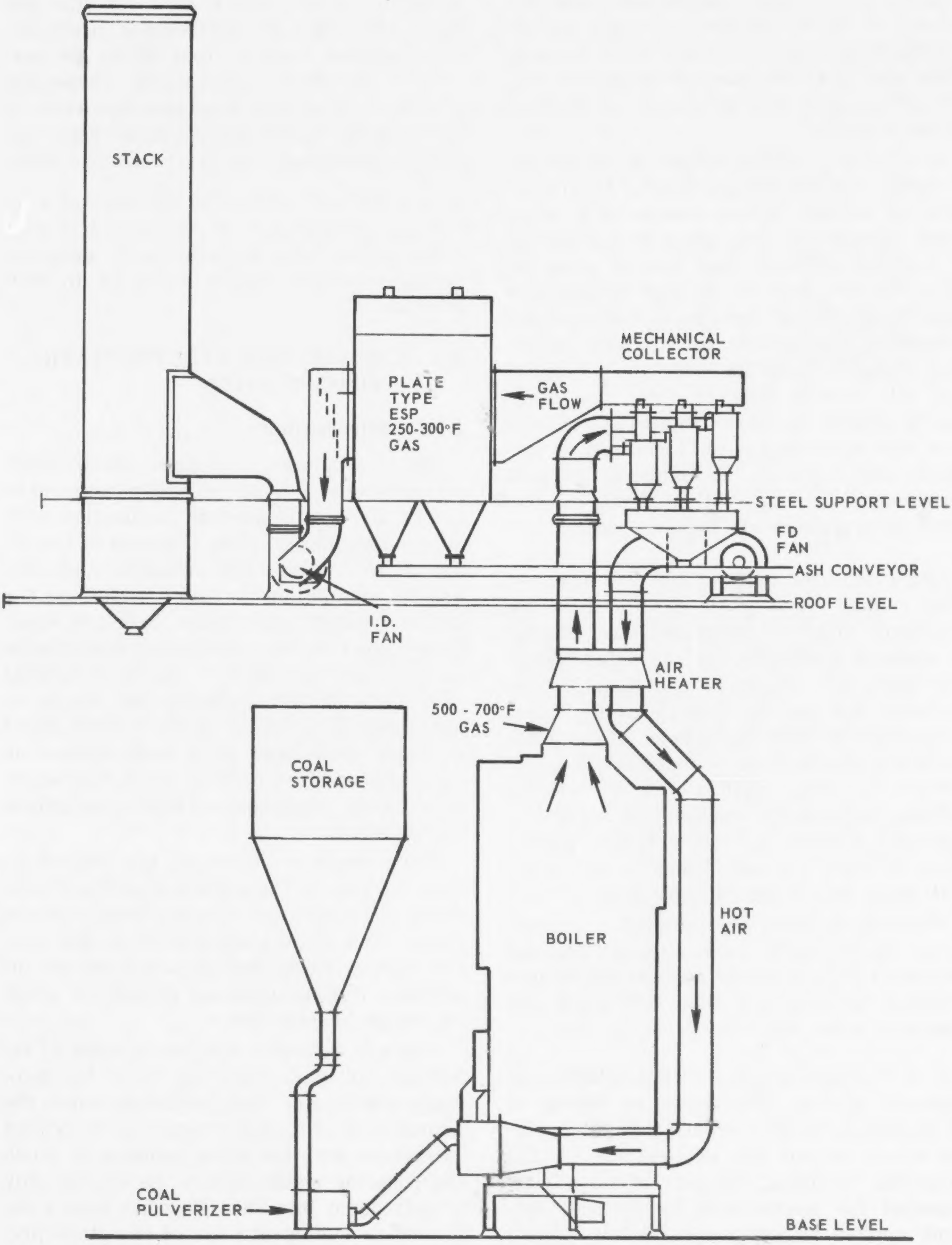

STACK
PLATE TYPE ESP 250-300°F GAS
GAS FLOW
MECHANICAL COLLECTOR
STEEL SUPPORT LEVEL
FD FAN
ASH CONVEYOR
ROOF LEVEL
I.D. FAN
AIR HEATER
500 - 700°F GAS
COAL STORAGE
BOILER
HOT AIR
COAL PULVERIZER
BASE LEVEL

Figure 4–53. Electrostatic precipitator installed after air heater in power plant steam generator system.

temperature from 220° to 350° F. The best precleaners seldom exceed 80 percent efficiency. Assuming an 80 percent cleanup, the electrostatic precipitator would have to collect 95 percent of the remaining particulate matter to achieve an overall efficiency of 99 percent. When soot is blown, particulate matter concentrations are well in excess of average emission levels.

A recently installed collection system locates the electrostatic precipitator before, instead of behind, the air heater on a large steam generator. The collector is rated at 99 percent efficiency and handles gases at from 600° to 700° F. In this temperature range resistivity of particles is favorable for collection; particularly for fly ash generated from low sulfur coals and residual fuel oil. Installations of this type must handle greater volumes of gases and, therefore, are more expensive. Long-term evaluations are necessary to compare the performance of this unit with cold-side electrostatic precipitators of the same rating.

4.5.8.2 Integrated Steelmaking Operations—High-voltage electrostatic precipitators are frequently used in integrated steel plants. A common application is the detarring of coke oven gas. Wet-type electrostatic precipitators are used for final cleaning of blast furnace gases. Exit loadings as low as 0.005 grain per standard cubic foot have been reported for this application.[103-106] High-voltage electrostatic precipitators applied to sintering strands reportedly reduce particulate emission concentrations to less than 0.04 grain per standard cubic foot.[107-109]

Precipitator equipment applied to oxygen-lanced open hearths, basic oxygen furnaces, and electric arc furnaces reduces particulate emission levels to less than 0.05 grain per standard cubic foot.[104, 108, 110-115]

4.5.8.3 Cement Industry—Electrostatic precipitator system efficiencies in excess of 98 percent have been reported for dry-process rotary cement kiln applications.[116] Efficiencies exceeding 99 percent have been reported for electrostatic precipitator systems applied to wet-process rotary cement kilns.[116]

4.5.8.4 Kraft Pulp Mills—The electrostatic precipitator is a common gas cleaning device used on kraft mill recovery furnaces. A survey of 50 plants indicated that the rated efficiency of electrostatic precipitators installed ranged from 90 to 98 percent.[117] In some applications efficiencies of at least 99 percent have been reported.[118] Electrostatic precipitators have been applied to emissions from kraft mill lime kilns.

4.5.8.5 Sulfuric Acid—The efficiency of electrostatic precipitators in removing acid mist from contact-type sulfuric acid manufacturing processes ranges from 92 to 99.9 percent.[119]

4.6 LOW-VOLTAGE ELECTROSTATIC PRECIPITATORS

4.6.1 Introduction

The low-voltage, two-stage, electrostatic precipitator is a device originally designed to purify air, and is used in conjunction with air-conditioning systems. Cleaning of incoming air at hospitals and industrial and commercial installations is also a major use for the low-voltage precipitator, and it is sometimes called an air-conditioning precipitator or electronic air filter.[120] As an industrial particulate matter collector, the device is used for the control of finely divided liquid particles discharged from such sources as meat smokehouses, asphalt paper saturators, pipe coating machines, and high-speed grinding machines.

Low-voltage precipitators are limited almost entirely to the collection of liquid particles, which will drain readily from collector plates. Two-stage precipitators cannot control solid or sticky materials, and become ineffective if concentrations exceed 0.4 grain per standard cubic foot.

There is a limited number of ways of removing collected materials from the two-stage precipitator. This limitation causes the primary use of the equipment to be restricted to systems with low grain loadings in which the collector plates need to be cleared only at infrequent intervals. This has been a deterrent to widespread use of two-stage precipitators in air pollution control. Also, electrostatic precipitators do not collect or remove gases or vapors responsible for objectionable odors and eye irritation.

4.6.2 Major Components of Low-Voltage Electrostatic Precipitators

The feature of the low-voltage precipitator (Figure 4–54) that distinguishes it from the high-voltage electrostatic precipitator is the separate ionizing zone located ahead of the collection plates.[121] The ionizing stage consists of a series of fine (0.007-inch diameter) positively charged wires equally spaced at distances of from 1 to 2 inches from parallel grounded tubes or rods. A corona discharge between each wire and a corresponding tube charges the particles suspended in the air flowing through the ionizer. The direct-current potential applied to the wires amounts to 12 or 13 kilovolts. Positive polarity is regularly used to minimize the formation of ozone.

The second stage consists of parallel metal plates usually less than an inch apart. In some designs, alternate plates are charged positively and negatively, each to a potential of 6 or 6½ kilovolts direct current, so that the potential difference between adjacent plates is 12 or 13 kilovolts.

In other cases, plates are alternately charged to a positive potential of 6 to 13 kilovolts and grounded. (The lower voltages are used with closely spaced plates.) This arrangement is shown in Figure 4–54. The illustration shows particles entering at the left, receiving a positive charge in the ionizer, and being collected at the negative plates in the second stage. Liquids drain by gravity to a pan located beneath the plates. Rapping or shaking is not employed, primarily because of the close spacing of plates.

The package unit shown in Figure 4–55 is used to collect oil mist from grinding machines.[122] Oil droplets agglomerate on the plates and drain to the bottom. Because solids or viscous liquids will not drain freely, systems removing such materials have to be shut down occasionally for cleaning of the plates to prevent arcing.

Semiviscous materials can be collected by the low-voltage precipitator if an adequate washing system is provided. The frequency of washing will depend on the inlet loading and the characteristics of the collected particulate matter.

4.6.3 Auxiliary Equipment

Pretreatment of particles may be required to improve their electrical properties before they enter the precipitator. The system shown in Figure 4–56 includes a low-pressure scrubber, mist eliminator, and tempering coil to control temperature and humidity. Removal of large particles by the scrubber allows longer operating periods without shutdown for cleaning of the electrostatic precipitator. Mist eliminators remove water droplets and prevent excessive sparkover. Heating coils allow flexibility in setting optimum conditions. For many materials, a relative humidity greater than 50 percent in the gas stream is beneficial.

4.6.4 Design Parameters

When a low-voltage electrostatic precipitator is used in conjunction with air conditioning, velocities range between 5 and 10 feet per second (fps). However, for pollution control purposes, where the particulate loadings are much higher, the superficial gas velocity through the plate collector section should not exceed 1.7 fps. The relationship between air velocity and collection efficiency is illustrated by the Penney equation which assumes streamline flow. The Penney (1937) equation for two-stage precipitation is:

$$F = \frac{wL}{vd}$$

where:

F = efficiency expressed as a decimal.
w = drift velocity, feet per second.
L = collector length, feet.
v = gas velocity through collector, feet per second.
d = distance between collector plates, feet.

The upper limit for streamline flow through these two-stage precipitators is 600 feet per minute (fpm). Mechanical irregularities in units now manufactured may reduce this upper limit.

The effect of gas velocity on collection efficiency for several industrial operations is

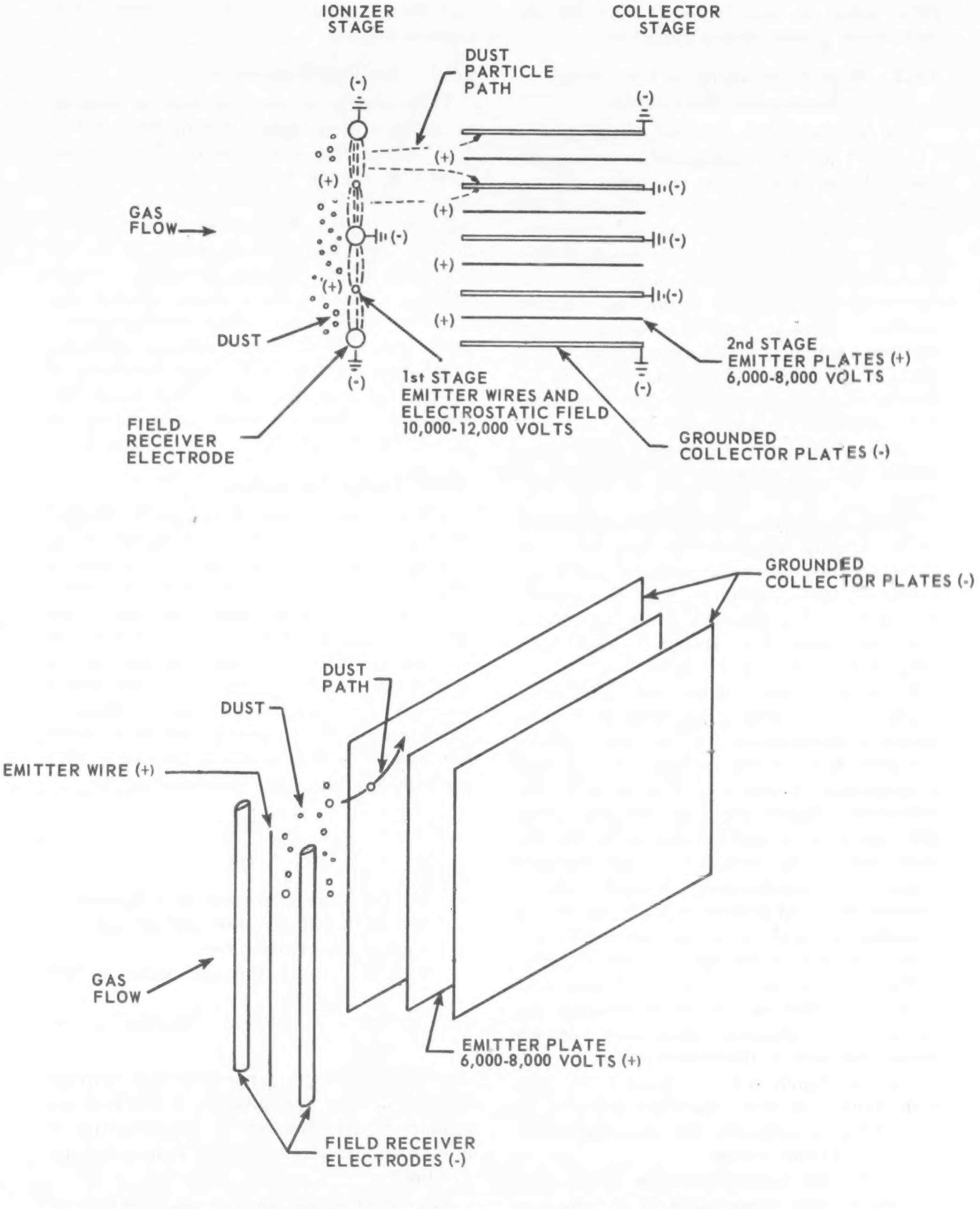

IONIZER STAGE
COLLECTOR STAGE
DUST PARTICLE PATH
(-)
(+)
GAS FLOW
DUST
FIELD RECEIVER ELECTRODE
1st STAGE EMITTER WIRES AND ELECTROSTATIC FIELD 10,000-12,000 VOLTS
2nd STAGE EMITTER PLATES (+) 6,000-8,000 VOLTS
GROUNDED COLLECTOR PLATES (-)
GROUNDED COLLECTOR PLATES (-)
DUST PATH
DUST
EMITTER WIRE (+)
GAS FLOW
EMITTER PLATE 6,000-8,000 VOLTS (+)
FIELD RECEIVER ELECTRODES (-)

FIGURE 4-54. Operating principle of two-stage electrostatic precipitator.

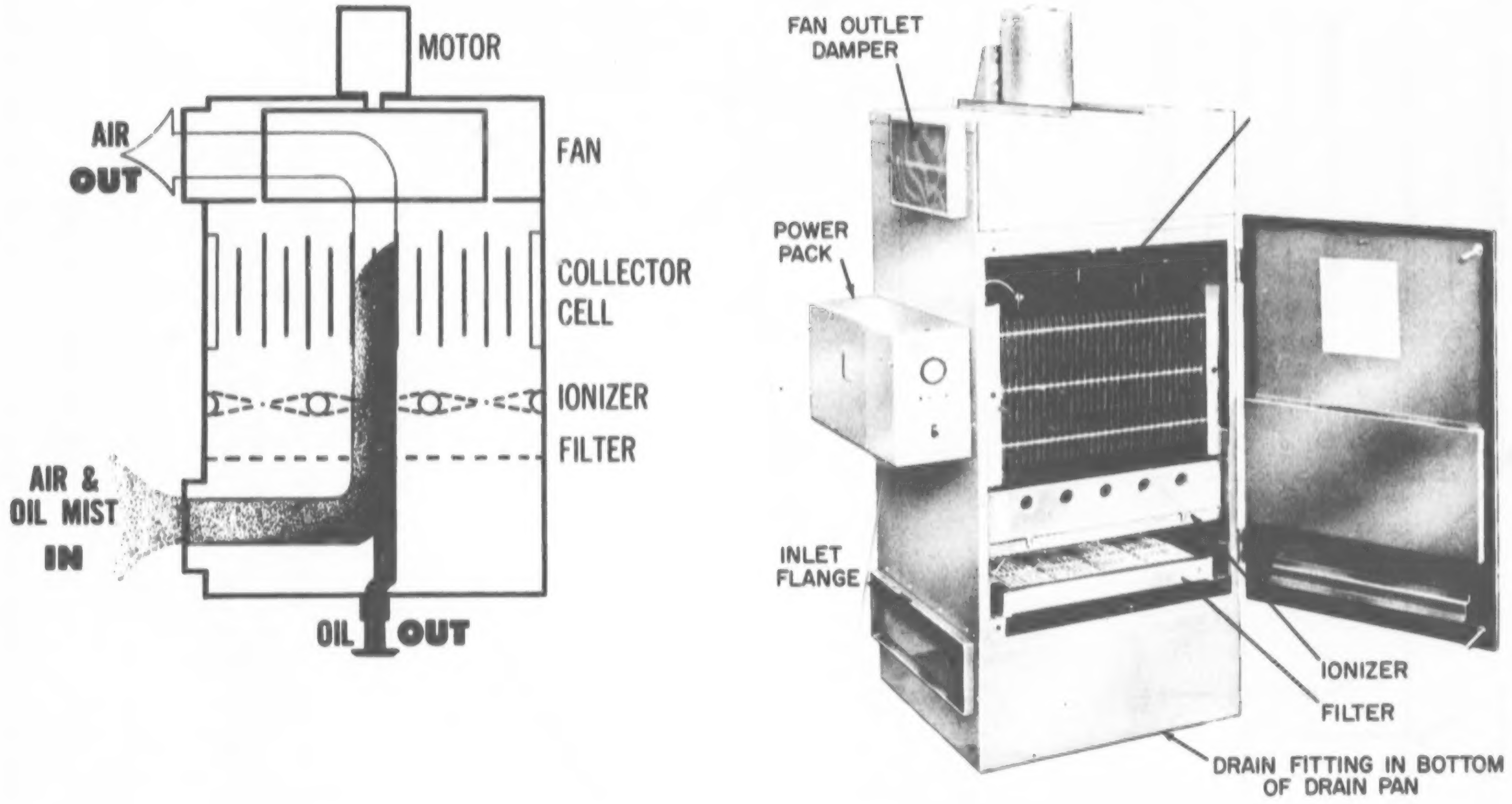

MOTOR
AIR OUT
FAN
COLLECTOR CELL
IONIZER
FILTER
AIR & OIL MIST IN
OIL OUT
FAN OUTLET DAMPER
POWER PACK
INLET FLANGE
IONIZER
FILTER
DRAIN FITTING IN BOTTOM OF DRAIN PAN

FIGURE 4–55. Two-stage precipitator used to control oil mist from machining operations.
(Courtesy of Westinghouse Electric Corporation)

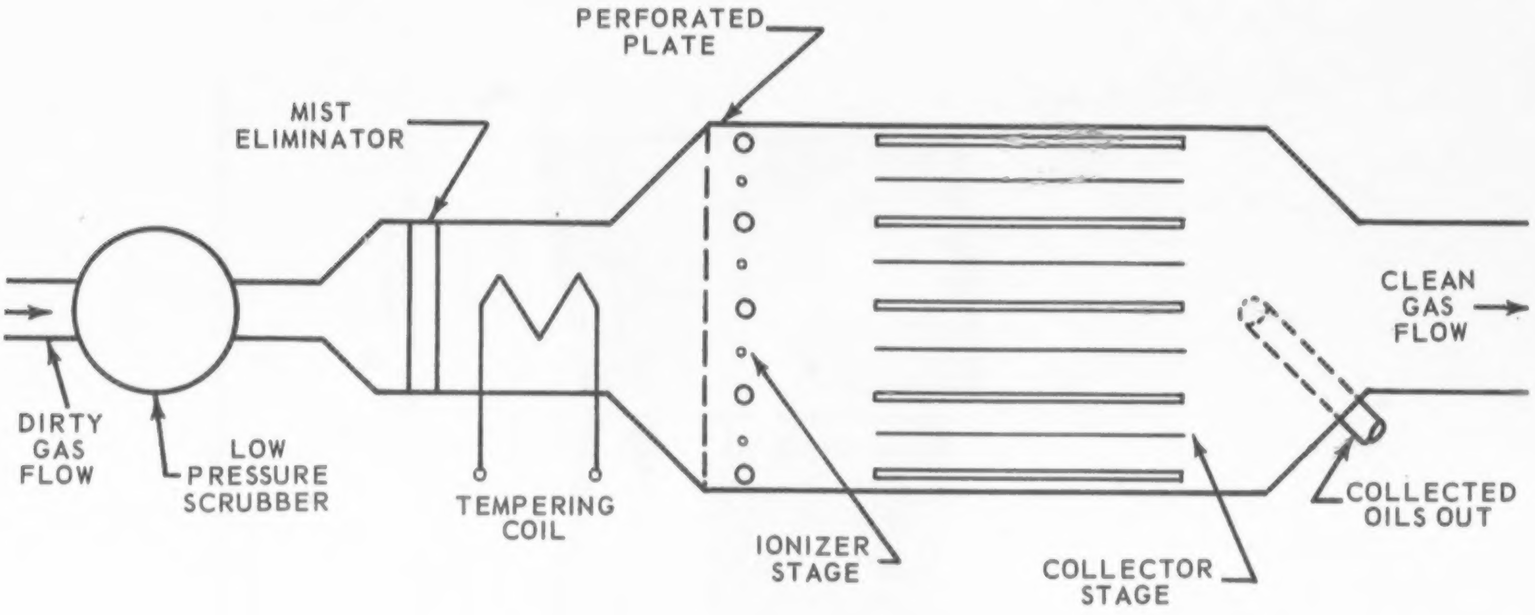

PERFORATED PLATE
MIST ELIMINATOR
DIRTY GAS FLOW
LOW PRESSURE SCRUBBER
TEMPERING COIL
IONIZER STAGE
COLLECTOR STAGE
CLEAN GAS FLOW
COLLECTED OILS OUT

FIGURE 4–56. Two-stage electrostatic precipitator with auxiliary scrubber, mist eliminator, tempering coil, and gas distribution plate (top view).

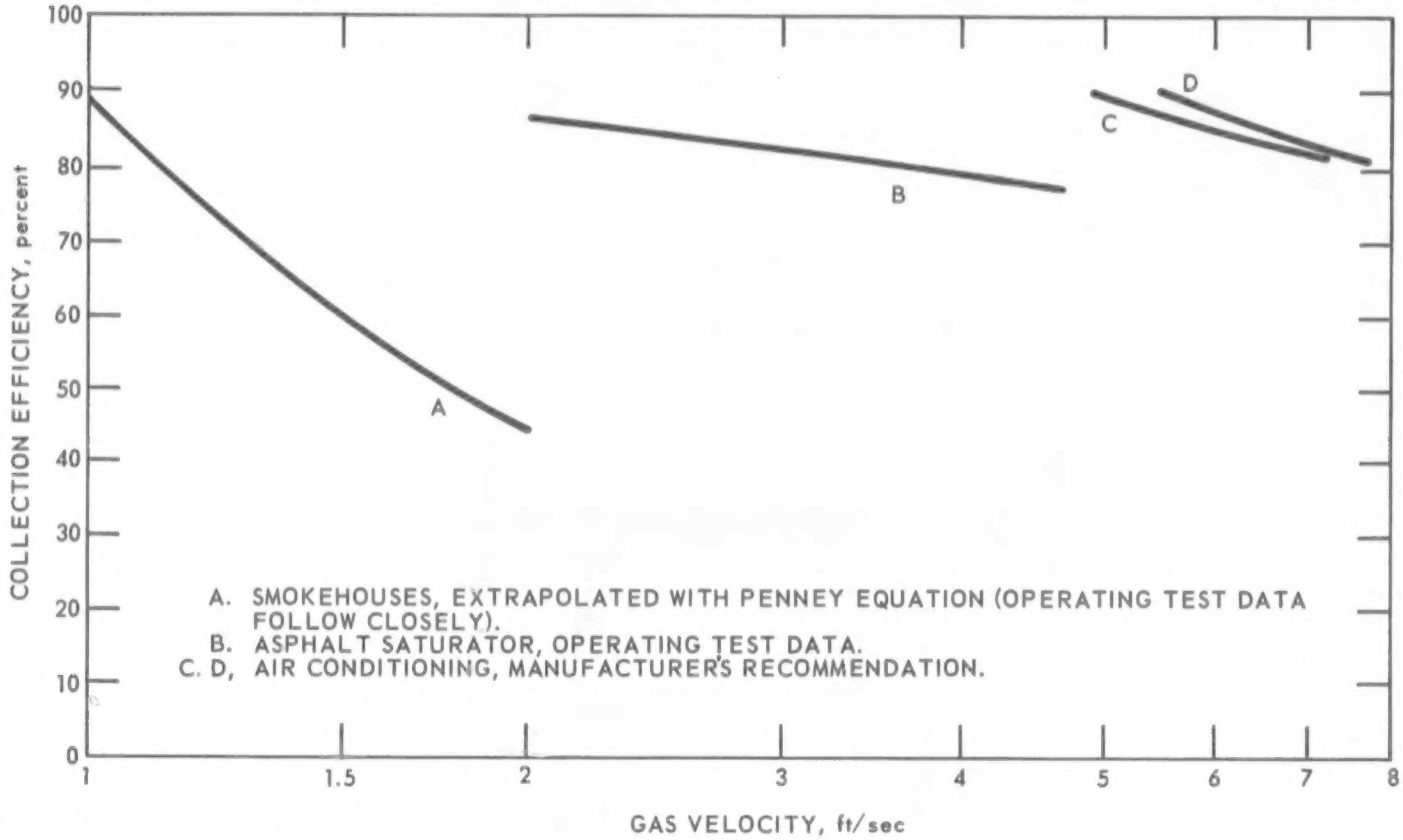


FIGURE 4–57. Efficiency of two-stage precipitator as function of velocity for several industrial operations.

shown in Figure 4–57. Efficiencies of 80 percent and greater are shown for the collection of oil mist at asphalt paper saturators and for air conditioning applications. Collection efficiencies ranging from 60 to 80 percent are possible for meat smokehouses at a velocity of 1.5 fps. For smokehouses, collection decreases rapidly at higher velocities. Test data for typical installations are shown in Table 4–7.

The practical voltage limit for low-voltage precipitators is 18 kilovolts. Most units operate at 10 to 13 kilovolts. Current flow under these conditions is small (4 to 10 milliamperes). The collecting plates are usually energized at 5.5 to 6.5 kilovolts, but poten-

Table 4-7.—INDUSTRIAL OPERATION OF TWO-STAGE PRECIPITATORS[121]

Contaminant source	Contaminant type	Ionizing voltage	Number of ionizer banks	Collector voltage	Efficiency wt percent	Velocity, fpm	Inlet concentration gr/scf
Tool grinding	Oil aerosol	13,000	1	6,500	90	333	......
Meat smokehouse	Wood smoke, vaporized fats.	13,000	2	6,500	90	60	0.103
Meat smokehouse	Wood smoke, vaporized fats.	10,000	1	5,000	50	50	1.181
Deep fat cooking	Bacon fat aerosol	13,000	2	6,500	(75 percent opacity reduction)	68	....
Asphalt saturator (roofing paper.	Oil aerosol	12,000	1	6,000	85	145	0.384
Muller-type mixer	Phenol-formaldehyde resin.	13,000	1	6,500	87	75	0.049

tials up to 13 kilovolts are possible. Actual current flow is small because no corona exists between the plates.

The degree of ionization may be increased by increasing the number of ionizing electrodes, either by decreasing spacing or by installing a second set of ionizing wires in series. Because decreased spacing requires reduced voltage to prevent sparkover, there appears to be an advantage in the series arrangement. Decreased spacing, however, lowers first cost and space requirements.

Low-voltage precipitators of standard design for capacities up to 20,000 cfm are supplied by manufacturers in preassembled units requiring only external wiring and duct connections. The installed weight of the precipitator is approximately 80 pounds per square foot of cross-sectional area measured perpendicular to the gas flow. These standard units are usually sized so that the air flow for air pollution applications is about 100 fpm.

4.6.5 Materials of Construction

The standard material used in the construction of low-voltage precipitator collector cells is aluminum. The precipitator housing is usually made of galvanized steel and frames are of aluminum. Where washing is to be frequent and even mildly corrosive conditions exist, ionizer wires should be made of stainless steel.

4.6.6 Typical Applications of Low-Voltage Electrostatic Precipitators

Applications of low-voltage precipitators to air pollution control have developed slowly since 1937 when the first installation was successfully used to collect ceramic overspray from pottery glazing operations. Other applications have been the collection of oil mist from high-speed grinding machines and the cleaning of gases from deep fat fryers, asphalt saturators, rubber curing ovens, and carpet mill dryers. See Table 4-7 for operational data.

4.6.6.1 Machining Operations—High speed grinding machines generate mist from cutting oils, which must be vented from the working area. Package units of the type shown in Figure 4-55 are used to collect the mist. A filter is provided ahead of the precipitator to remove metal chips and any other large particles. Concentrations of solids and tars are usually low enough to be flushed from the plates with the collected oil droplets.

4.6.6.2 Asphalt Saturators—In the manufacture of roofing paper, low-voltage electrostatic precipitators are used to remove the steam-distilled organic materials from hot liquid asphalt. Moisture evolved from the paper carries oil from the process. Oils that are collected flow readily from the plates of the electrostatic precipitator; only occasional cleaning is required.

4.6.6.3 Meat Smokehouses—Smokehouses are used by meat packing houses to cook and smoke a variety of products. During the cooking cycle, exhaust products are reasonably innocuous and exhaust gases can be discharged directly to the atmosphere. Smoke generated from hardwood sawdust contains liquid aerosols, most of which are partially oxidized organics. In addition to aerosols, odorous, eye-irritating gases and vapors are discharged in exhaust products.

Two-stage precipitators have been used with limited success to control visible aerosols from smokehouses. All such operations use the design of Figure 4–56 with a scrubber, mist eliminator, and tempering coil. Under optimum operation, these units have reduced visible emissions to about 10 percent opacity. Maintenance is a problem, however and the exhaust gases have a strong odor and a lachrymose character.

The collected particles are principally tars and gums. When the unit is warm (120 to 180° F), at least some of these tars drain from the plates. When the plates are not cleaned regularly, arcing occurs in the collector section, particularly near the lower edges of the plates.

4.6.6.4 Other Applications—Two-stage precipitators offer the promise of a low-cost control device for such operations as rubber curing and carpet mill drying, where oil mists are generated. Conceivably, these devices can be used wherever the liquid separates easily from the plates and wherever other considerations such as odors and eye irritants are not a problem.

4.6.7 Air Distribution

Proper air distribution through the precipitator is essential for efficient collection. Precipitators are usually installed with horizontal air flow and frequently in positions requiring abrupt changes in gas flow preceding the unit. Installations of this type can result in turbulent and uneven flow with high local velocities, leading to low overall efficiencies.

Where a straight section of at least 8 duct diameters is not available ahead of the precipitator, mechanical means for balancing the air flow must be used. Several types of distribution baffles and turning vanes have been devised. The most effective device has been found to be one or more perforated sheet metal plates fully covering the cross section of the plenum preceding the ionizers. The optimum open area for the plate is about 40 percent of the cross-section.

4.6.8 Maintenance

To assure optimum performance, the internal parts of the precipitator must be kept clean enough to prevent arcing. In addition, voltages have to be held within proper ranges, and plate and wire spacings have to be maintained within reasonably small tolerances.

The frequency of internal washing will depend on the application. High particulate loadings in the gas stream and sticky materials present the greatest problems. On the other hand, two-stage precipitators can be operated indefinitely where relatively clean, free-flowing oils are collected.

4.7 FABRIC FILTRATION

4.7.1 Introduction

One of the oldest and most positive methods for removing solid particulate contaminants from gas streams is by filtration through fabric media.[123] The fabric filter is capable of providing a high collection efficiency for particles as small as 0.5 micron and will remove a substantial quantity of particles as small as 0.01 micron.[124]

With a fabric filter, the dust-bearing gas is passed through a fabric in such a manner that dust particles are retained on the upstream or dirty-gas side of the fabric while the gas passes through the fabric to the downstream or clean-gas side. Dust is removed from the fabric by gravity and/or mechanical means.[125] The fabric filters or bags are usually tubular or flat.

The structure in which the bags hang is known as a baghouse. The number of bags may vary from one to several thousand. The baghouse may have one compartment or many so that one may be cleaned while others are still in service. Figure 4–58 illustrates one type of baghouse.

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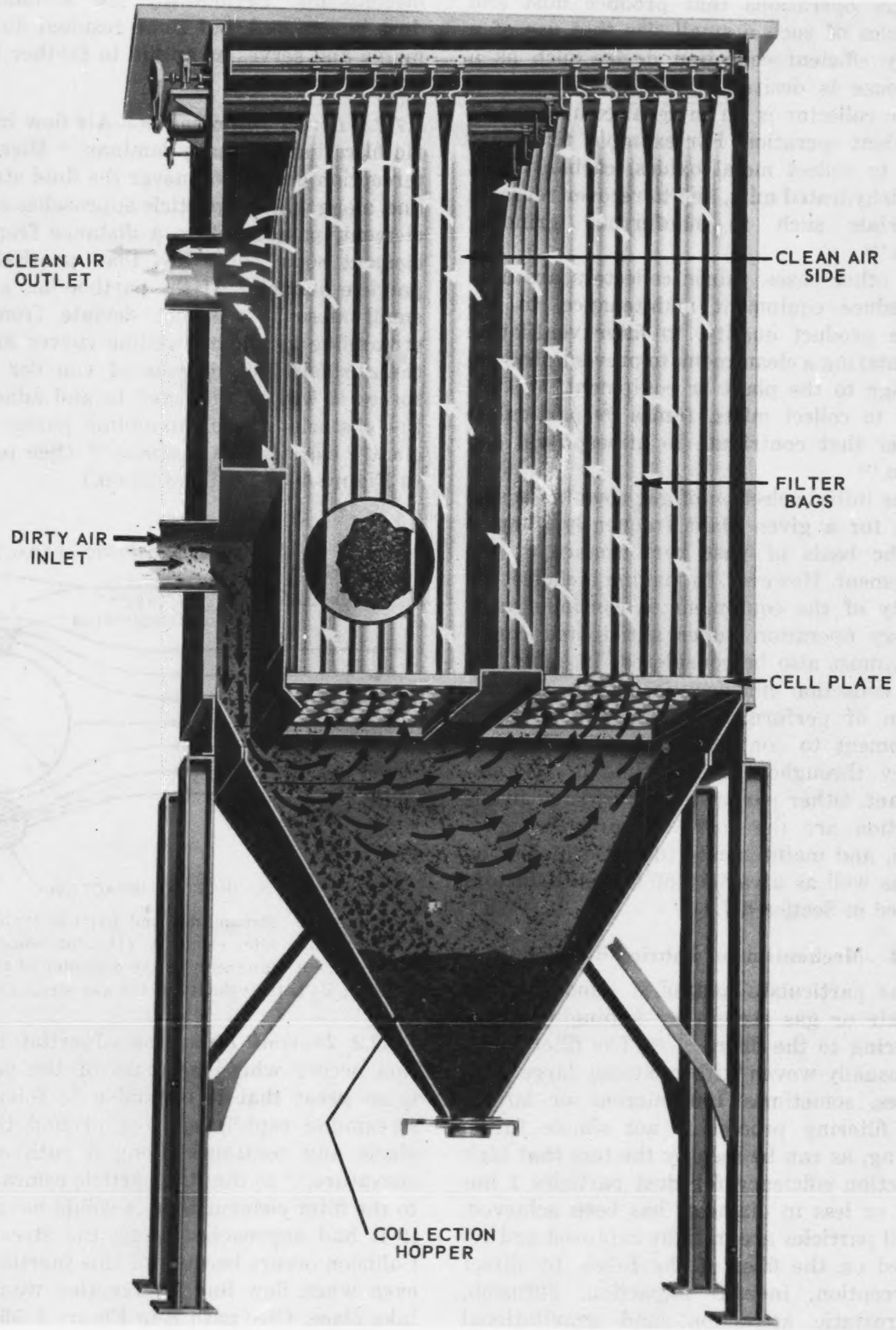

CLEAN AIR OUTLET
CLEAN AIR SIDE
FILTER BAGS
DIRTY AIR INLET
CELL PLATE
COLLECTION HOPPER

FIGURE 4–58. Typical simple fabric filter baghouse design.

4.7.1.1 Range of Application—Approximately 80 percent of all manufacturing plants contain operations that produce dust and particles of such a small size that use of a highly efficient collection device such as a baghouse is desirable.[123] In many cases, a fabric collector is an integral component of the plant operation. For example, filters are used to collect metal oxides, carbon black, and dehydrated milk, and to recover reusable materials such as nonferrous grinding dusts.[126]

In other cases, fabric collectors are used to reduce equipment maintenance, to improve product quality, to filter ventilation air entering a clean room, to prevent physical damage to the plant or equipment, and usually to collect mists, fumes or particulate matter that contribute to atmospheric pollution.[126]

The initial selection of gas cleaning equipment for a given plant frequently is made on the basis of past performance of the equipment. However, in making a choice, the ability of the equipment to continue satisfactory operation under anticipated conditions must also be considered. In short, design collection efficiency is not the sole criterion of performance. The ability of the equipment to continue high collection efficiency throughout its lifetime is also important. Other parameters considered in the selection are the costs of purchase, operation, and maintenance (detailed in Section 6), as well as a variety of technical factors (listed in Section 4.7.4).

4.7.2 Mechanisms of Fabric Filtration

The particulate matter is removed from the air or gas stream by impinging on or adhering to the fibers.[127, 128] The filter fibers are usually woven with relatively large open spaces, sometimes 100 microns or larger. The filtering process is not simple fabric sieving, as can be seen by the fact that high collection efficiency for dust particles 1 micron or less in diameter has been achieved. Small particles are initially captured and retained on the fiber of the fabric by direct interception, inertial impaction, diffusion, electrostatic attraction, and gravitational settling. Once a mat or cake of dust is accumulated, further collection is accomplished by mat or cake sieving as well as the above mechanisms. Periodically the accumulated dust is removed, but some residual dust remains and serves as an aid to further filtering.

4.7.2.1 Direct Interception—Air flow in fabric filtration is usually laminar.[129] Direct interception occurs whenever the fluid streamline, along which a particle approaches a filter element, passes within a distance from the element equal to or less than one half the particle diameter. If the particle has a very small mass it will not deviate from the streamline as the streamline curves around the obstacle, but because of van der Waal forces it will be attracted to and adhere to the obstacle if the streamline passes sufficiently close to the obstacle.[130] (See path A in Figure 4–59 for illustration.)

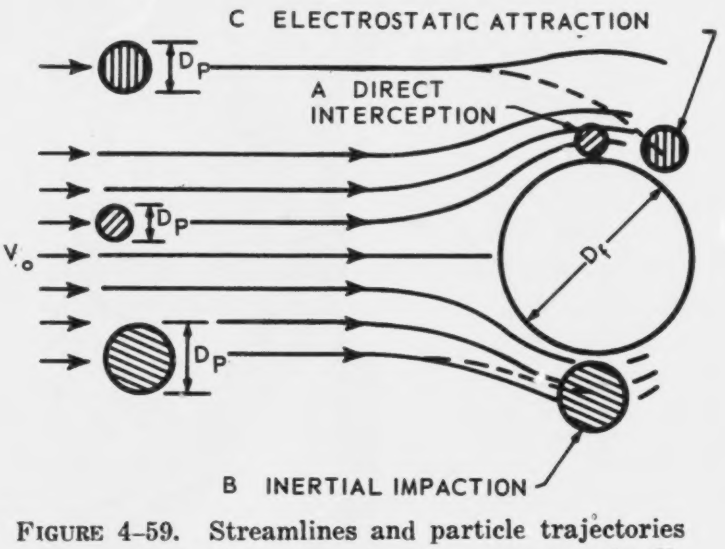


FIGURE 4–59. Streamlines and particle trajectories approaching filter elements. (D_f represents the filter element diameter; D_p the diameter of the particles; V_0 is the velocity of the gas stream.)

4.7.2.2 Inertial Impaction—Inertial impaction occurs when the mass of the particle is so great that it is unable to follow the streamline rapidly curving around the obstacle and continues along a path of less curvature,[130] so that the particle comes closer to the filter element than it would have come if it had approached along the streamline. Collision occurs because of this inertia effect even when flow line interception would not take place. (See path B in Figure 4–59). Impaction is not a significant factor in collecting particles of 1 micron diameter or less. Impaction is considered significant for the collection of particles of two microns diameter and becomes the predominant factor as particle size increases.[131]

4.7.2.3 Diffusion—For particles ranging in size from less than 0.01 to 0.05 micron diameter, diffusion is the predominant mechanism of deposition. Such small particles do not follow the streamline because collision with gas molecules occurs, resulting in a random Brownian motion that increases the chance of contact between the particles and the collection surfaces. A concentration gradient is established after the collection of a few particles, and acts as a driving force to increase the rate of deposition. Lower air velocity increases efficiency by increasing the time available for collision and therefore the chance of contacting a collecting surface.[131]

4.7.2.4 Electrostatic Attraction—Electrostatic precipitation will result from electrostatic forces drawing particles and filter element together whenever either or both possess a static charge. (See path C in Figure 4–59.) These forces may be either direct, when both particle and filter are charged; or induced, when only one of them is charged. Such charges are usually not present unless deliberately introduced during the manufacture of the fiber. Electrostatics assists filtration by providing an attraction between the dust and fabric, but it also affects particle agglomeration, fabric cleanability, and collection efficiency. A triboelectric series of filter fabrics may be useful in selecting fabric with desirable electrostatic properties.[132]

4.7.2.5 Gravitational Settling—Settling of particles by gravity onto the filter surface may result from particle weight as the particle passes through the filter. A simple method of judging the usefulness of a mechanism, based on particle size, is shown in Table 4–8.[133]

4.7.3 Filter Resistance

Two forms of resistance, clean cloth resistance and dust mat resistance, affect the design of baghouses containing fabric filters.

Table 4–8.—CONTROL MECHANISM FOR PARTICLE SIZE COLLECTION[133]

Primary collection mechanism	Diameter of particle, microns
Direct interception	>1
Impingement	>1
Diffusion	0.001 to 0.5
Electrostatic	0.01 to 5
Gravity	>1

4.7.3.1 Clean Cloth Resistance—The resistance to air flow offered by clean filter cloth is determined by the fiber of the cloth and the manner in which the fibers are woven together. A tight weave offers more resistance than a loose weave at the same air flow rate and, because the air flow is laminar, resistance varies directly with air flow. One of the characteristics of filter fabrics frequently specified is the American Society for Testing and Materials (ASTM) permeability, which expresses the air volume in cubic feet per minute passing through a square foot of clean new cloth with a pressure differential of 0.50 inch water gauge. The usual range of values is from 10 to 110 cfm per square foot.[134] With normal design conditions, the resistance of the clean cloth does not exceed 0.10 inch of water gauge and is often less. The average flow rate in use for an operating cloth is 1.5 to 3.0 cubic feet per minute per square foot of woven cloth. This is known as the air-to-cloth ratio or the filtering velocity in feet per minute.[134]

4.7.3.2 Dust Mat Resistance—The pressure drop of the dust mat at the end of any elapsed time is related to the concentration of dust in the gas stream, the mass density of the gas, and the face velocity of the gas through the fabric by the equation:

$$(\Delta p_t)_{mat} = K\left(\frac{G\rho g v^2 t}{C}\right)$$

where:

$(\Delta p_t)_{mat}$ = pressure drop of the dust mat, inches of water

t = elapsed time, seconds

G = dust concentration in gas stream, lb/ft^3

ρ = mass density of gas, slugs/ft^3

g = acceleration of gravity, ft/sec^2

v = face velocity of gas through the fabric, ft/sec
K = resistance coefficient
C = dimensional constant

The values of K, the resistance coefficient modified to include a factor for conversion of dust cake thickness to mass with constant viscosity, must be determined experimentally. C is a dimensional constant adjusted as required for the actual units used.[131, 135]

K values are usually determined by means of a scale model unit either in the laboratory or in the field. Care must be exercised in applying such results to a full-scale unit.[136] If a vertical bag is used, elutriation of particles may occur so that the true value of K varies with time and position on the bag.[136] The measured value of K is an average value that may not be the same when the scale or the configuration is changed. This is borne out by failure of some full-scale units to function as anticipated on the basis of pilot studies.

Table 4-9 gives K values for a number of dusts.[135] These data were obtained by laboratory experiments using an air flow of 2 cubic feet per minute through 0.2 square foot of cloth area (equivalent to a filtering velocity of 10 ft/min). The tests were terminated at a maximum pressure differential of 8 inches of water column.

Investigators have found that K varies as a power function of the filter velocity,[137] and velocities greater than 2.3 ft./min. seriously affect the K value of the fly ash being studied.[138] These recent studies indicate that K values listed in Table 4-9 should be used only for estimates. Further research is needed to define more precisely the factors affecting the resistance coefficients of filter cakes. The values in Table 4-9 may be used when such limitations are considered.

The pressure drop across the collected dust increases uniformly with time, indicating a linear relationship between resistance and the thickness of the accumulated dust mat. The data clearly show a trend of increasing resistance with decreasing particle size. In a full-scale baghouse, particularly if relatively long vertical bags are used, a substantial amount of elutriation can be expected.[139] The dust-laden gas usually enters the filter bag at the bottom and travels upward. As the gas filters through the cloth, its upward velocity decreases so that only very fine dust remains airborne to be deposited on the upper portion of the bag. Because the actual pressure loss through the bag must be the

Table 4-9.—FILTER RESISTANCE COEFFICIENTS (K) FOR INDUSTRIAL DUSTS ON WOVEN FABRIC FILTERS[135]

Dusts	Filter resistance coefficients (K) [a] for particle size smaller than						
	20 mesh [b, c]	140 mesh [b, c]	375 mesh [b, d]	90 μ [d, e]	45 μ [d, e]	20 μ [f]	2 μ [f]
Granite	1.58	2.20	----------	----------	----------	19.8	----------
Foundry	0.62	1.58	3.78	----------	----------	----------	----------
Gypsum	----------	----------	6.30	----------	----------	18.9	----------
Feldspar	----------	----------	6.30	----------	----------	27.3	----------
Stone	0.96	----------	----------	6.30	----------	----------	----------
Lampblack	----------	----------	----------	----------	----------	----------	47.2
Zinc oxide	----------	----------	----------	----------	----------	----------	15.7[g]
Wood	----------	----------	----------	6.30	----------	----------	----------
Resin (cold)	----------	0.62	----------	----------	----------	25.2	----------
Oats	1.58	----------	----------	9.60	11.0	----------	----------
Corn	0.62	----------	1.58	3.78	8.80	----------	----------

[a] K = inches water gauge per pound of dust per square foot per foot per minute of filtering velocity.
[b] U.S. standard sieve.
[c] Coarse, smaller than 20 mesh or 140 mesh.
[d] Medium, smaller than 350 mesh, 90 μ or 45 μ.
[e] Theoretical size of silica; no correction made for materials having different densities.
[f] Fine, smaller than 20 μ or 2 μ.
[g] Flocculated material, not dispersed, size actually larger.

same through all areas, the volume and filtering velocity through some portions of the bag reach high values. Investigators[136] found that local filtering velocities vary by a factor of 4 or more throughout a single filter bag. This, in turn, may lead to collapse or puncture of the filter cake.[139] Punctures (small holes in the dust mat) are usually self-repairing because the increased air flow through the small area of low resistance brings more dust with it. Collapse of the filter cake, on the other hand, is a shift in cake structure to a more compacted condition with a greater resistance.

Collapse and puncture of the filter cake are phenomena caused by excessive filtering velocities. Some dust is embedded and remains in the interstices of the cloth when puncture or collapse occurs so that normal cleaning does not completely remove this dust. The embedded dust "blinds" or plugs the fabric pores to such an extent that the fabric resistance becomes permanently excessively high. Once begun, blinding becomes worse rapidly. For example, transient local filtering velocities of 100 ft/min through areas of puncture were found when the average filtering velocity was only 0.75 ft/min.[139]

4.7.3.3 Effect of Resistance on Design—Resistance of the cloth filter and dust cake cannot be divorced from the total exhaust system. The operating characteristics of the exhaust blower and the duct resistance determine the ways in which increases in the baghouse resistance affect the gas rate. If the blower performance curve is steep, the gas flow rate may be reduced only slightly when the resistance of the filter bags changes markedly.[131] Some variation in resistance and air volume occurs normally in all baghouses. Proper design requires that the volume be sufficient to capture the emissions at the source when the system resistance is maximum and the gas volume minimum. To prevent blinding of fabric from particle impaction, the filter ratio must not be excessive immediately after cleaning when the pressure drop is at a minimum and the air volume at a maximum.

4.7.4 Equipment Description and Design

The selection or design of industrial dust collection equipment requires consideration

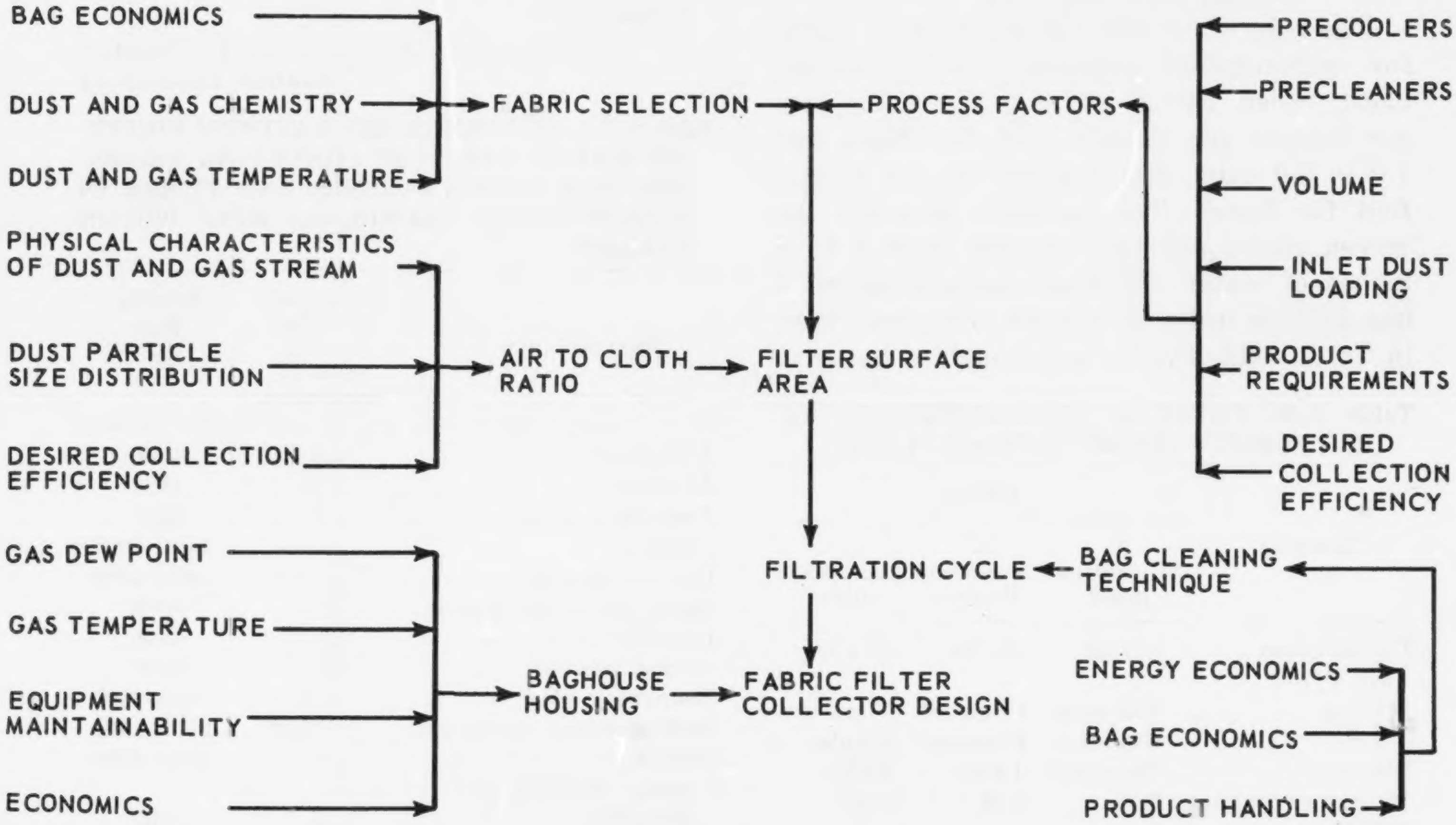

BAG ECONOMICS
DUST AND GAS CHEMISTRY
DUST AND GAS TEMPERATURE
FABRIC SELECTION
PROCESS FACTORS
PRECOOLERS
PRECLEANERS
VOLUME
INLET DUST LOADING
PRODUCT REQUIREMENTS
DESIRED COLLECTION EFFICIENCY
PHYSICAL CHARACTERISTICS OF DUST AND GAS STREAM
DUST PARTICLE SIZE DISTRIBUTION
DESIRED COLLECTION EFFICIENCY
AIR TO CLOTH RATIO
FILTER SURFACE AREA
FILTRATION CYCLE
BAG CLEANING TECHNIQUE
GAS DEW POINT
GAS TEMPERATURE
EQUIPMENT MAINTAINABILITY
ECONOMICS
BAGHOUSE HOUSING
FABRIC FILTER COLLECTOR DESIGN
ENERGY ECONOMICS
BAG ECONOMICS
PRODUCT HANDLING

FIGURE 4-60. System analysis for fabric filter collector design.

of many factors. Figure 4–60 illustrates the complex nature of the final selection of a fabric collector. Exhaust system design considerations include:

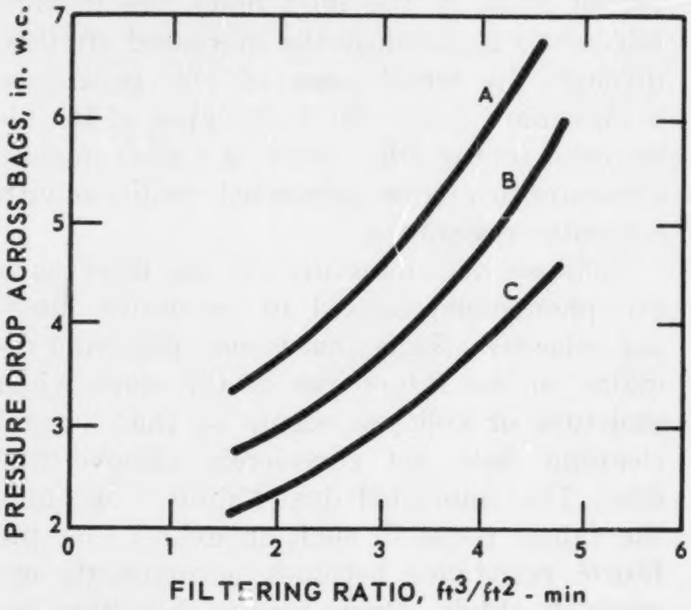
1. Determination of the minimum volume to be vented from the basic equipment.
2. Estimation of the maximum desirable resistance.
3. Selection of the blower operating point that will provide the minimum required volume at the maximum system resistance.
4. Estimation of the minimum resistance for the condition immediately after a thorough cleaning of the filter bags.
5. Determination of a second operating point on the blower characteristic curve for the clean bag condition.
6. Determination of the minimum filtering area required by the maximum filtering velocity permissible for the particular dust or fume being collected.
7. Rechecking of the calculations, with the filtering area thus determined, to assure compatibility.

The rule of thumb for air-to-cloth ratios for conventional baghouses with woven-cloth, fabric filters is 1.5 to 3.0 cubic feet per minute per square foot for dusts and 1.0 to 2.0 cubic feet per minute per square foot for fumes. The pressure drop for the woven cloths normally ranges from 2 to 8 inches of water. Physical characteristics of bag fabrics tested in a pilot plant are given in Table 4–10. Typical relationships between filter ratio and pressure drop across bags for the three fabrics in Table 4–10 [140] are shown in Figure 4–61.[140]

Table 4–10.—PHYSICAL CHARACTERISTICS OF BAG FABRICS TESTED IN PILOT PLANT[140]

Material	Fabric		
	A Siliconized glass	B Siliconized Dacron	C Siliconized glass
Thread count	54×52	73×68	65×35
Yarn Type:			
Warp	Filament	Filament	Filament
Fill	Filament	Filament	Staple
Weave	Crowfoot	Twill	Twill
Weight, oz/sq yd	9.36	4.59	9.00
ASTM permeability	15–20	25–35	60–80

Typical filter ratios and dust conveying velocities for various dusts and fumes collected in woven cloth bags are shown in Table 4–11.[141]



Note: A and C are siliconized glass fabrics, B is a siliconized Dacron fabric.

FIGURE 4–61. Pressure drop versus filter ratio for fabrics on 60-minute cleaning cycle for electric furnace dust.

(Courtesy of the Journal of the Air Pollution Control Association)

Table 4–11.—RECOMMENDED MAXIMUM FILTERING RATIOS AND DUST CONVEYING VELOCITIES FOR VARIOUS DUSTS AND FUMES IN CONVENTIONAL BAGHOUSES WITH WOVEN FABRICS[141]

Dust or fumes	Maximum filtering ratios, cfm/ft^2 cloth area	Branch pipe velocity, fpm
Abrasives	3.0	4500
Alumina	2.25	4500
Aluminum oxide	2.0	4500
Asbestos	2.75	3500–4000
Baking powder	2.25–2.50	4000–4500
Batch spouts for grains	3.0	4000
Bauxite	2.5	4500
Bronze powder	2.0	5000
Brunswick clay	2.25	4000–4500
Buffing wheel operations	3.0–3.25	3500–4000
Carbon	2.0	4000–4500
Cement crushing and grinding	1.5	4500
Cement kiln (wet process)	1.5	4000–4500

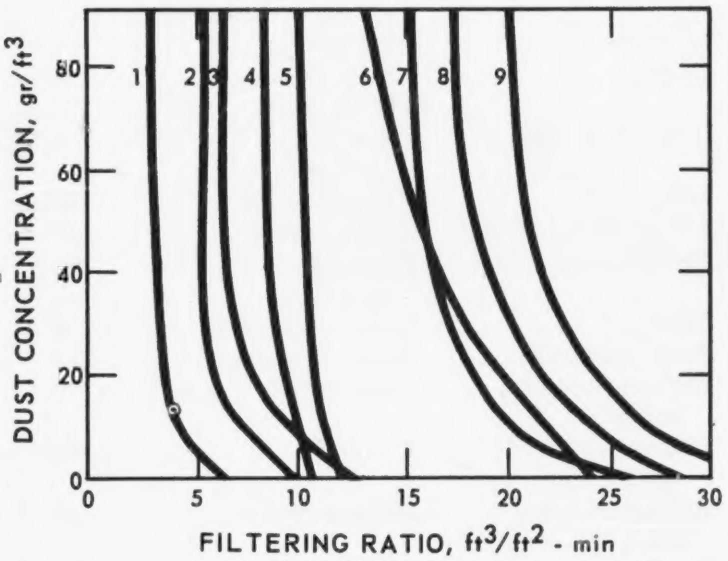
Table 4-11 (Continued).—RECOMMENDED MAXIMUM FILTERING RATIOS AND DUST CONVEYING VELOCITIES FOR VARIOUS DUSTS AND FUMES IN CONVENTIONAL BAGHOUSES WITH WOVEN FABRICS[141]

Dust or fumes	Maximum filtering ratios, cfm/ft² cloth area	Branch pipe velocity, fpm
Ceramics	2.5	4000–4500
Charcoal	2.25	4500
Chocolate	2.25	4000
Chrome ore	2.5	5000
Clay	2.25	4000–4500
Cleanser	2.25	4000
Cocoa	2.25	4000
Coke	2.25	4000–4500
Conveying	2.5	4000
Cork	3.0	3000–3500
Cosmetics	2.0	4000
Cotton	3.5	3500
Feeds and grain	3.25	3500
Feldspar	2.5	4000–4500
Fertilizer (bagging)	2.4	4000
Fertilizer (cooler, dryer)	2.0	4500
Flint	2.5	4500
Flour	2.5	3500
Glass	2.5	4000–4500
Granite	2.5	4500
Graphite	2.0	4500
Grinding and separating	2.25	4000
Gypsum	2.5	4000
Iron ore	2.0	4500–5000
Iron oxide	2.0	4500
Lampblack	2.0	4500
Lead oxide	2.25	4500
Leather	3.5	3500
Lime	2.0	4000
Limestone	2.75	4500
Manganese	2.25	5000
Marble	3.0	4500
Mica	2.25	4000
Oyster shell	3.0	4500
Packing machines	2.75	4000
Paint pigments	2.0	4000
Paper	3.5	3500
Plastics	2.5	4500
Quartz	2.75	4500
Rock	3.25	4500
Sanding Machines	3.25	4500
Silica	2.75	4500
Soap	2.25	3500
Soapstone	2.25	4000
Starch	2.25	3500
Sugar	2.25	4000
Talc	2.25	4000
Tobacco	3.5	3500
Wood	3.5	3500

The rule of thumb for air-to-cloth ratios for reverse jet baghouses with felted or napped woven fabric filters is 10 to 16 cubic feet per minute per square foot of cloth for dust, and 6 to 10 cubic feet per square foot of cloth for fumes. Table 4-12 shows typical filter ratios of fabrics used for various dusts and fumes being collected in reverse jet baghouses.[142]

A typical range of dust loading for woven bag filters is from 0.1 to 10 grains per cubic foot of gas. Higher concentrations of particulate matter in some industries are removed by a pre-cleaning device, such as a low efficiency cyclone. Maximum dust loading reported for felted bag filters with reverse jet or pulse jet cleaning is 80 grains per cubic foot. Figure 4-62 presents dust loading versus filter ratio data for typical products.[143]

4.7.4.1 Baghouse Design—Many design considerations for handling waste gases from



KEY

1. MAGNESIUM TRISILICATE
2. CARBON BLACK
3. STARCH DUST
4. RESINOX
5. DIATOMACEOUS EARTH
6. KAOLIN
7. CEMENT OR LIMESTONE DUST
8. COAL DUST
9. LEATHER BUFFING DUST

FOR NUMBERS 1 THROUGH 6, 99.94 - 99.99 PERCENT PASSING 325 MESH. FOR NUMBERS 7 AND 8, 95 PERCENT PASSING 200 MESH. NUMBER 9, 60 MESH AVERAGE.

FIGURE 4-62. Typical performance of reverse-jet baghouses using felted fabrics on a variety of dusts (dust load versus filtering ratio at 3.5 in. w.c. pressure drop).

(Courtesy of the Industrial Chemist magazine)

Table 4-12.—RECOMMENDED MAXIMUM FILTERING RATIOS AND FABRIC FOR DUST AND FUME COLLECTION IN REVERSE-JET BAGHOUSES[142]

Material or operation	Fabric	Filtering ratios, cfm/ft²
Aluminum oxide	Napped cotton	11
Bauxite	Cotton sateen	10
Carbon, calcined	Napped cotton, wool felt.	8 [a]
Carbon, green	Orlon felt	7
Carbon, banbury mixer.	Wool felt	8
Cement, raw	Cotton sateen	9
Cement, finished	Cotton sateen	10
Cement, milling	Cotton sateen	8
Chrome, (ferro) crushing.	Cotton sateen	10
Clay, green	Cotton sateen	10
Clay, vitrified silicious.	Cotton sateen	12
Enamel, (porcelain)	Napped cotton	12
Flour	Cotton sateen	14 [a]
Grain	Wool felt, cotton sateen.	16
Graphite	Wool felt	7 [a]
Gypsum	Cotton sateen, orlon felt.	10
Lead oxide fume	Orlon felt, wool felt.	8 [a]
Lime	Napped cotton	10
Limestone (crushing)	Cotton sateen	10
Metallurgical fumes	Orlon felt, wool felt.	10 [a]
Mica	Napped cotton	11
Paint pigments	Cotton sateen	10
Phenolic molding powders.	Cotton sateen	10
Polyvinyl chloride (PVC).	Wool felt	10 [a]
Refractory brick sizing (after firing).	Napped cotton	12
Sandblasting	Napped cotton, wool felt.	6-8 [a]
Silicon carbide	Cotton sateen	9-11
Soap and detergent powder.	Dacron felt, orlon felt.	12 [a]
Soy bean	Cotton sateen	14
Starch	Cotton sateen	10
Sugar	Cotton sateen, wool felt.	10 [a]
Talc	Cotton sateen	11
Tantalum fluoride	Orlon felt	6 [a]
Tobacco	Cotton sateen	12
Wood flour	Cotton sateen	10
Wood sawing operations.	Cotton sateen	12
Zinc, metallic	Orlon felt, dacron felt.	11
Zinc oxide	Orlon felt	8 [a]
Zirconium oxide	Orlon felt	8

[a] Decrease 1 cfm/ft² if dust concentration is high or particle size is small.

various operations are the same regardless of the process involved. However, this is not necessarily true of baghouse type—a most important design decision—which ranges from the open-pressure type to the closed, welded, fully insulated baghouse. Generally the type of baghouse required is dictated by the moisture in the waste gas. The higher the dew point, the greater the precaution that must be taken to prevent condensation which can moisten the filter cake, plug the cloth, and corrode the housing and hoppers. Three designs, open pressure, closed pressure, and closed suction are used in fabric filter baghouse construction.[144] The cost of the open pressure system is the least of the three; that of the closed suction system is the greatest.

Open pressure—An open pressure baghouse, in which the fan is located on the dirty gas side of the system, can be operated with open sides as long as protection from the weather is provided. Under some circumstances, a completely open baghouse is satisfactory,[144] and allows hotter inlet gas temperatures to be used because the cooling is better in an open baghouse. Better cooling allows lower temperature filter media to be used with higher inlet gas temperatures than might otherwise be possible.[131] In an open pressure system, the blower must handle the entire dust load, which causes the blower to wear substantially. Thus, maintenance cost is higher than that for a blower on the clean gas side of a baghouse. Because air flows from the inside of the filter bags, bag replacement is facilitated because a leaky bag is easier to locate. The open pressure unit is

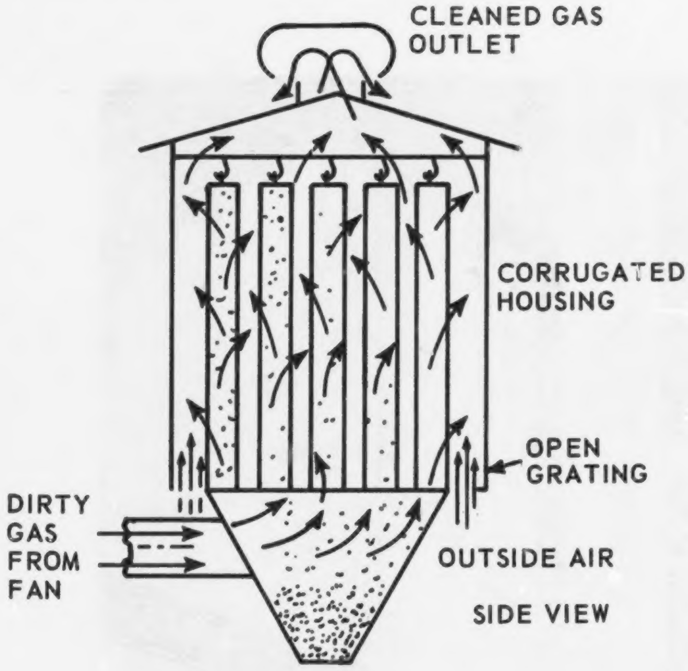


FIGURE 4-63. Open pressure baghouse.

normally constructed with corrugated steel or asbestos cement walls. It may have open gratings at the cell plate level and may not require hopper insulation. Figures 4-63 and 4-64 illustrate the open pressure baghouse.[144, 145]

Closed pressure—A closed pressure baghouse is also constructed with the fan on the dirty gas side of the system, but the structure is closed.

The closed pressure unit is used for gases with high dew points and for toxic gases, that cannot be released at low elevations. Blower maintenance problems are identical to those of the open pressure baghouse. Asbestos cement walls without insulation are sometimes used to construct closed pressure baghouses. The floor of such a unit is closed and the hoppers are insulated. Figure 4-65 and 4-66 illustrate the closed pressure baghouse.[144, 145]

Closed suction—A closed suction baghouse is one in which the fan is located on the clean gas side of the closed, all-welded, air tight structure. The closed suction unit is used for gases with dew points between 165° F and 180° F. The floor of such a unit is closed and the structure walls and hopper are insulated, particularly for dew points in the upper range. Blower maintenance is cheaper because the blower is on the clean gas side of the system. The inspection for holes in the bag is difficult. Figures 4-67 and 4-68 illustrate the closed suction baghouse.[144, 145]

Structural considerations—Metal used to construct the baghouse walls and hoppers must be strong enough to withstand the pressure differentials involved. A pressure differential of 8 inches water column represents approximately 42 pounds per square foot. The total air pressure exerted on a side panel of a closed suction baghouse may be in excess of 2 tons.[131]

Easy access to the baghouse interior must be provided to change bags and to perform maintenance. The open pressure unit has easy access to the cell plate at the bottom of the baghouse, even when the unit is operating. However, at the bag top level, the hot and possibly toxic gases prevent bag changing without taking the unit off stream. To overcome this difficulty, many units are furnished with internal partitions between compartments so an individual compartment can be isolated. Thus, the remaining compartments continue to filter while the one removed from service is maintained.

Hoppers are sized to hold the collected dust while or until it is removed for disposal. The slope of the sides of the hopper must be steep enough to permit the dust to slide or flow freely. The designer must also consider the possibility of bridging. Continuous removal of dust will help to prevent bridging of material, and will prevent operating difficulties with materials that become less fluid with time.

4.7.4.2 Fabric Filter Shape—Filter shape is dependent on the use to which the filter will be put. Two major bag shapes, the envelope (flat) and the tube, are used.

The envelope bag is illustrated in Figure 4-69.[145] Dust is collected on the outside of the bag, which is prevented from collapsing by the use of internal screens or frames. However, the internal screen complicates bag changing and the contact of the screen and fabric reduces cloth life. The envelope bag has the advantage of providing more filtering surface per volume than the tubular bag because of the close spacing of the envelopes. If the dust has a tendency to bridge, every

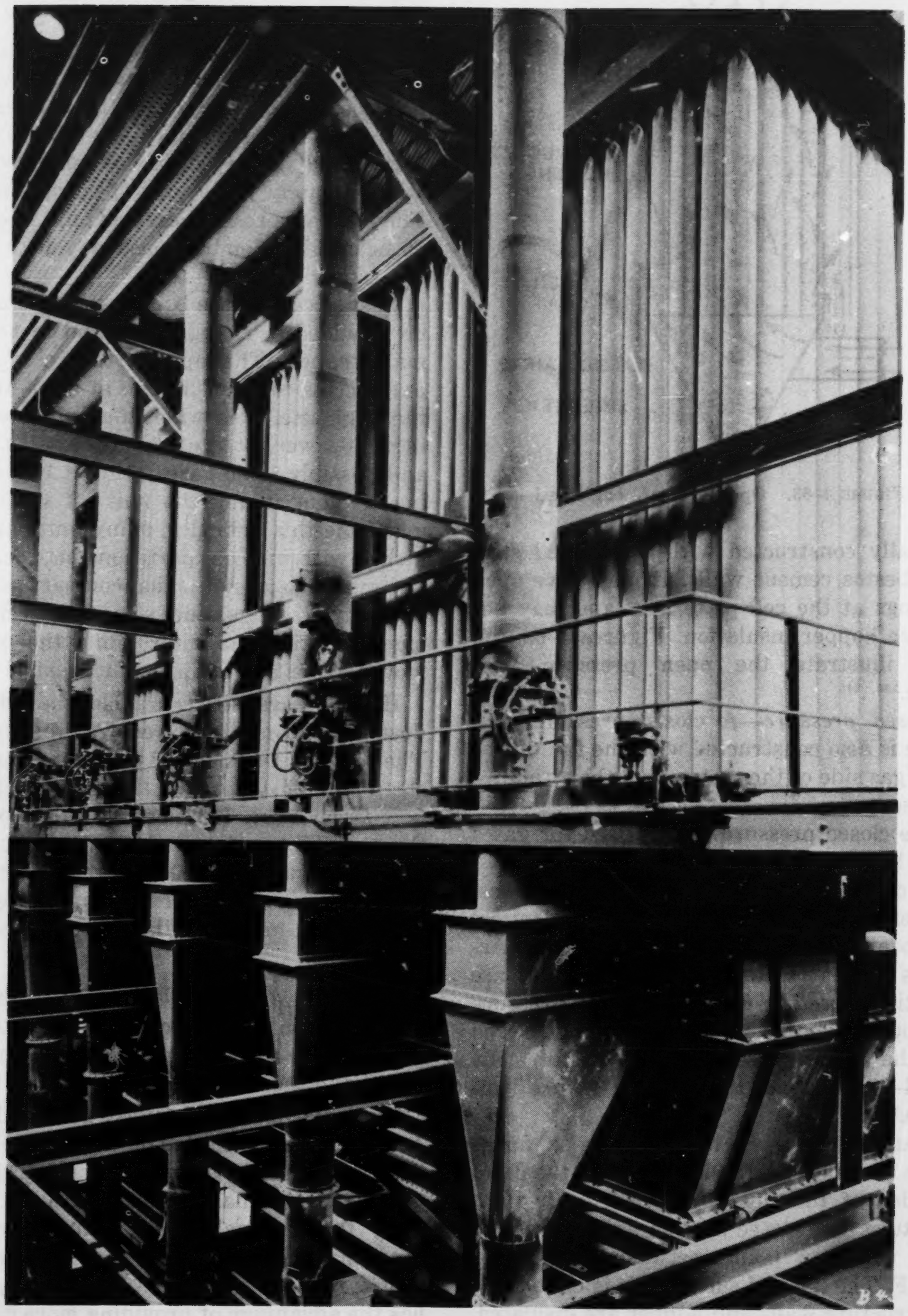


FIGURE 4-64. Open pressure baghouse unit showing installation without a separate clean gas housing. *(Courtesy of the Wheelabrator Corporation)*

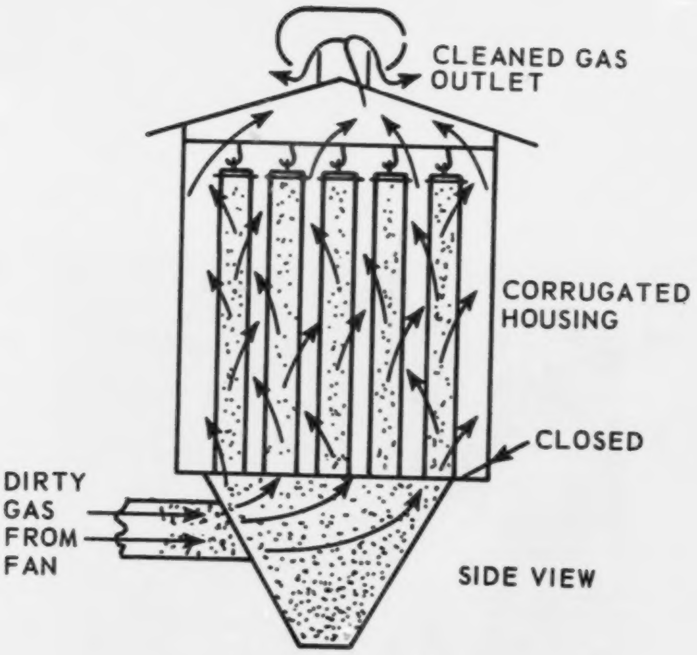


FIGURE 4-65. Closed pressure baghouse.

other bag may be removed to prevent plugging.

The tubular bag, illustrated in Figure 4-70, is open at one end and closed at the other.[145] Tubular bag design is more varied than flat bag design. Multi-bag and bottom or top entry uni-bag filters are in widespread use. Air flow may be either from the outside or inside.

A multi-bag is a group of either three or six tubular bags sewn together as shown in Figure 4-71.[145] Multi-bag suspension is limited to a top loop suspension. A disadvantage of the top loop suspension is the difficult adjustment required occasionally because of the multi-bag dimensional instability.

The uni-bag is a single tubular bag, not attached to other bags, into which gas may enter from the top or bottom. Bottom entry allows gas to enter from the hopper section and flow upwards into the filtering area as shown in Figure 4-72.[145]

Bottom entry allows pre-separation of the coarse particles in the hopper, and the fabric handles the suspended dust. Gas flows down in a top entry unit into the filtering area as shown in Figure 4-73.[145] The entire dust load passes through the entire tube of the top entry design before dust reaches the hopper. A cell plate ceiling, as well as a cell plate floor, increases the difficulty of adjusting top entry bags. The top entry baghouse creates a dead gas pocket in the hopper than can be a source of trouble because of condensation of water vapor in moisture-laden gases.

The direction of gas flow in tubular bags can be either inside out or outside in. If the direction is outside then a frame is inserted in the bag to prevent the bag from collapsing. Collecting the dust on the outside of the bag requires that the unit be inspected on the dirty gas side and increases the difficulty of bag replacement. Also, shorter bag life is experienced because of bag and frame contact.

4.7.4.3 Cloth Type—Two basic types of cloth are used in fabric filters. They are woven cloth or "cake" filter media, and felted cloth or "fiber" filter media.[146, 147]

Woven fabric acts as a support on which a layer of dust is deposited to form a microporous layer capable of removing additional particles by sieving and other basic filtration mechanisms.[123] Cake filtration is the most important removal mechanism when new filter cloth becomes thoroughly impregnated with dust. A wide variety of woven and felted fabrics are used in fabric filters. Clean felted fabrics are more efficient dust collectors than clean woven fabrics, but woven materials are capable of giving equal filtration efficiency after a dust layer accumulates on the surface. When new woven fabric is placed in service, visible penetration of dust may occur until the cake builds up. This takes a period of a few hours to a few days for industrial applications, depending on the dust loading and the nature of the particles. When dealing with extremely low grain loadings and fine dusts, fabrics may be precoated with asbestos floats or similar materials to form an artificial filter cake to prevent dust leakage.

Another method of reducing dust leakage in fabrics is based on the use of electrostatics. Electrostatic forces used in dust collecting mechanisms are explained in Section 4.7.2.4. Electrostatics not only assists filtration by providing an attraction between the dust and fabric but also may affect particle agglomeration, fabric cleanability and collection efficiency.

Electrostatic charges are induced in both fabrics and dusts by friction. The maximum charge and the charge dissipation rate are

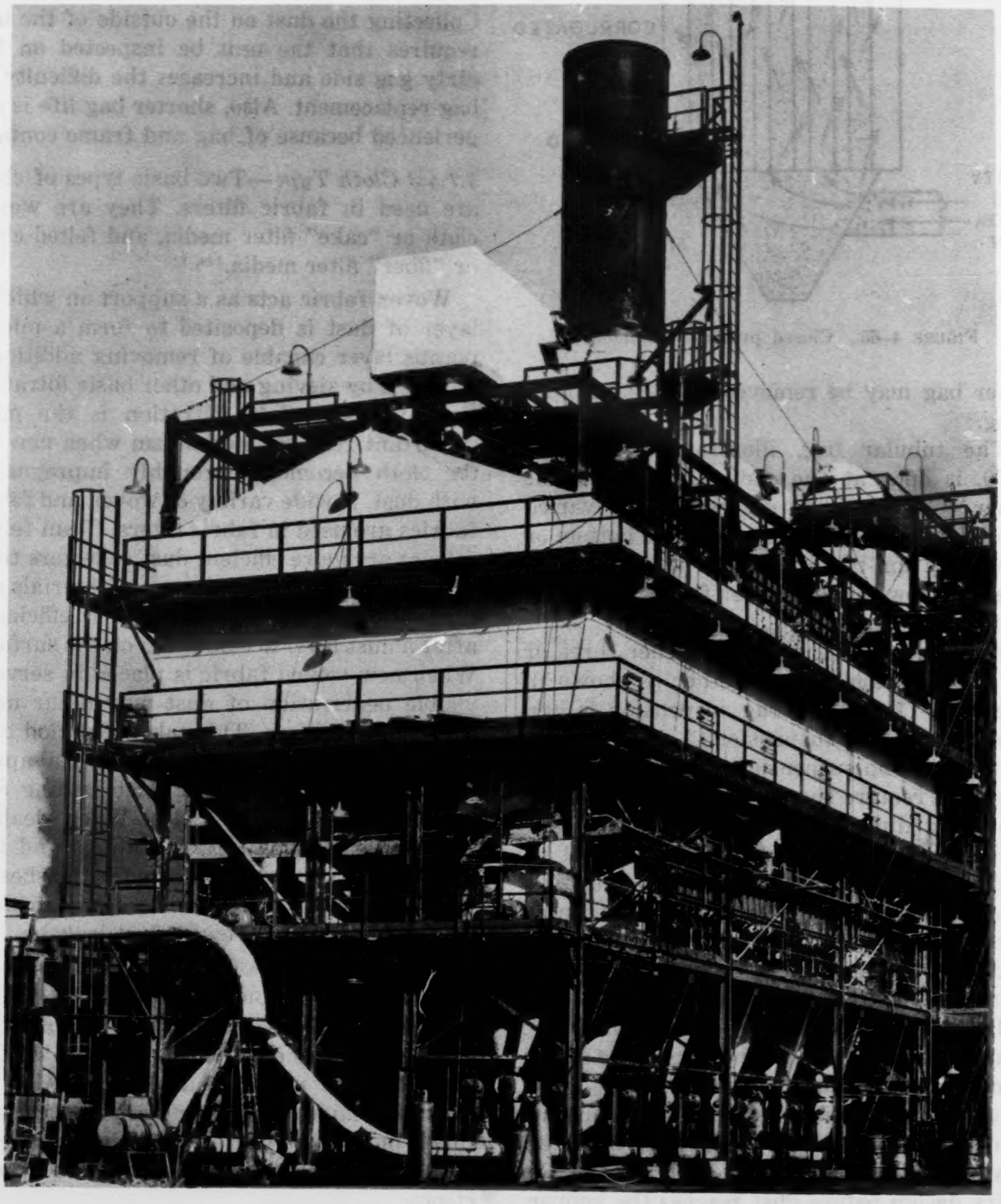


FIGURE 4-66. Closed pressure baghouse unit.

(Courtesy of the Wheelabrator Corporation)

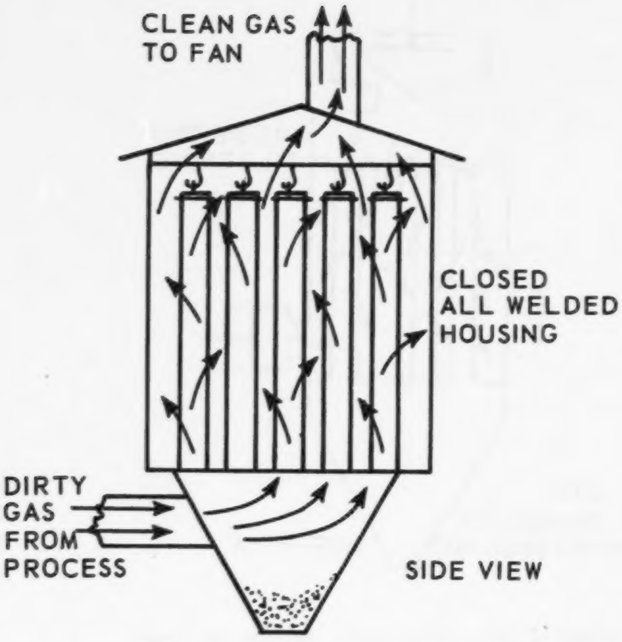


FIGURE 4-67. Closed suction baghouse.

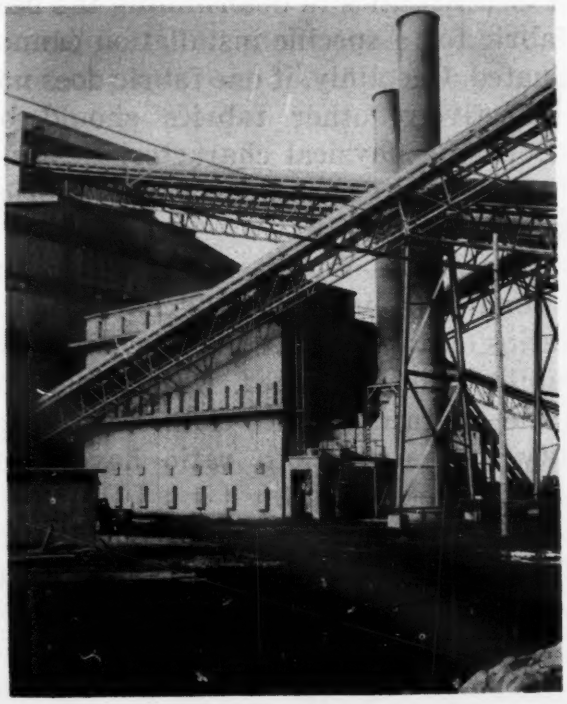


FIGURE 4-68. Closed suction concrete baghouse unit. *(Courtesy of the Wheelabrator Corporation)*

measured for each fabric and dust. Fabrics are arranged in relation to each other in a triboelectric series.[132] Attempts to develop such a series for dusts have not been successful.

Agglomeration of some charged dusts may be aided by selection of a fabric with an opposite charge. For example, a negatively charged dust would agglomerate with a positively charged fabric.

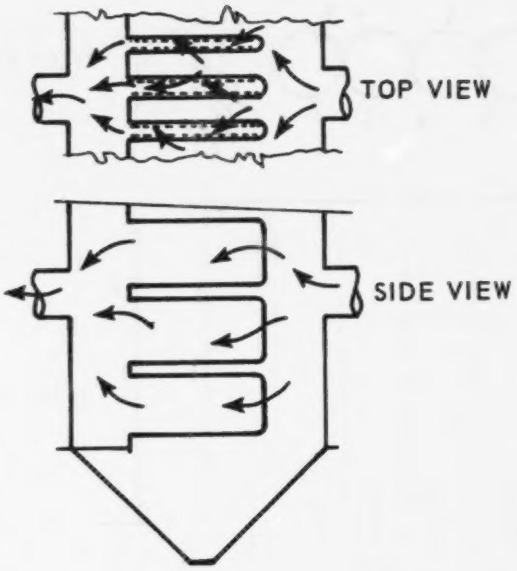


FIGURE 4-69. Typical flat or envelope dust collector bag.

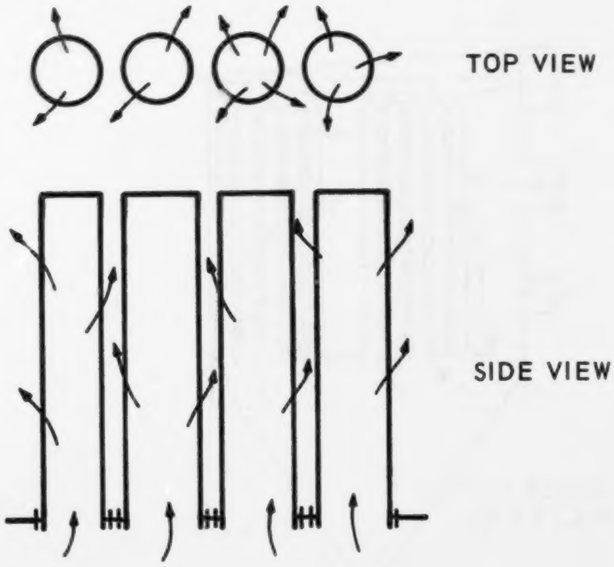


FIGURE 4-70. Typical round or tubular dust collector bag.

Dust leakage through a fabric may be reduced by maximizing the electrostatic differential between dust and fabric, thus maximizing the electrostatic attraction forces. Leakage may also be reduced by selecting a fabric with a low dissipation of electrostatic charge. A fast dissipation of charge reduces too quickly the electrostatic attraction between fabric and dust. When this occurs, fabric overcleaning during the cleaning cycle is possible with no residual dust remaining on fabric to act as a precoat.

Electrostatic charging has been introduced in some bonded fiberglass fabrics used for air conditioning installations. However, until

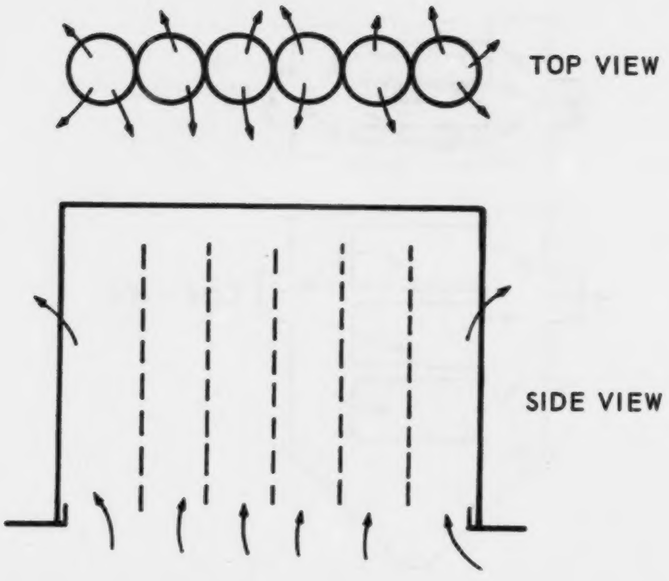


Figure 4–71. Typical multi-bag dust collection system.

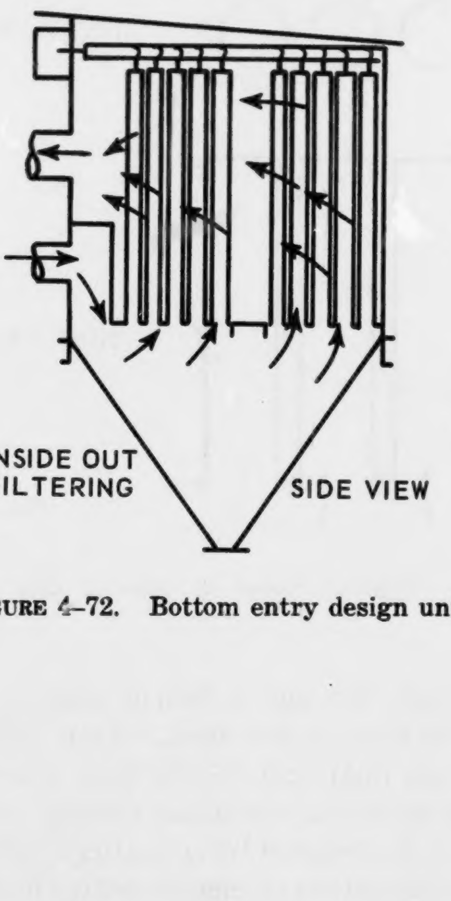


Figure 4–72. Bottom entry design uni-bag.

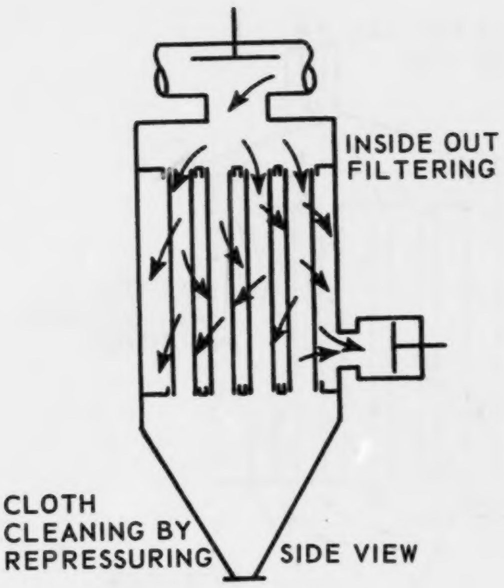


Figure 4–73. Top entry design uni-bag.

more information is available for large industrial fabric filters, the relative importance of electrostatics in determining the best filter fabric for a specific installation cannot be evaluated. Certainly, if one fabric does not work effectively, other fabrics should be tried. Both the physical characteristics and the electrostatic properties of the fabrics may serve as guides.

Woven fabrics—Woven fabric filters in conventional baghouses usually have air-to-cloth ratios of 1:1 to 5:1.[126, 130] Woven fabric permeability can be varied, which, in turn, varies the operating air-to-cloth ratio. Permeability and air-to-cloth ratio have been discussed in Section 4.7.3.1.

Woven fabric permeability or porosity is varied by using different yarns, fabric count, cloth weights (expresed as ounces per square yard), and weave patterns. The three basic forms of yarn used for woven fabrics are monofilament, multifilament, and spun-staple.[147] Monofilament yarn is a synthetic fiber made in a single, continuous filament. Multifilament yarn is made by twisting two or more monofilaments together. Spun-staple yarn is made by twisting short lengths of natural or synthetic fiber into a continuous strand. Warp is the yarn that runs lengthwise in a cloth and fill (pick) is the yarn that interlaces with warp yarn to form a woven fabric.[147] The count of a fabric is the number of warp and fill yarns per square inch in a woven fabric.

Another method for decreasing woven fabric porosity is to weave cloth from napped yarn or plied yarn. The napped yarn is made by abrading the surface of the filament yarn to produce a fuzzy, fibrous condition.[148] The plied yarn is made by twisting lighter weight yarns together in a single, continuous strand of yarn.[149] For example, a fabric made from 800 denier yarn (weight in grams of a single continuous strand of yarn, 9000 meters long) may be made from plied yarn by using four strands of 200 denier yarn. These four 200 denier strands of yarn may be twisted together to give the plied strand of yarn which may be used to weave the 800 denier cloth. The weight of the cloth remains unchanged while its dust retentivity is improved.

The basic weaves usually used for fabric filters are plain, twill, and sateen.[149] These are illustrated in Figure 4–74. The plain weave has a simple "one up and one down" construction. This construction permits maximum yarn interlacing per square inch, and, if woven tightly, allows high impermeability. If the count is lowered, this weave can be as open as desired. The plain weave is common in certain cotton ducks and many synthetic fibers.[149]

The twill weave is recognized by the sharp diagonal "twill" line formed by the passage of a warp yarn over two or more fill or pick yarns with the interlacing advancing one pick with each warp. In equivalent construction, twills have fewer interlacings than the plain weave and, hence, greater porosity, although this naturally depends on the count. Cotton and synthetic filter twills are commonly used.[149]

The sateen weave with even fewer pick interlacings, spaced widely and regularly, provides a smooth surface with increased porosity. These qualities make them particularly valuable in dust collection. Cotton fabrics in this weave are commonly known as sateens. Cotton sateen is probably more commonly used than any other fabric in fabric filters operated at ambient temperatures.

Dimensional stability is an important factor in filter fabric. Cotton and wool fabrics must be preshrunk, and synthetics are usually given a corresponding treatment known as "heat-setting".[131] This process contributes to a more even balance of warp and filling yarn tension, controls porosity, and virtually eliminates shrinkage. Dimensional stability may be lost if the fabric is subjected to temperatures near that used in the original heat-setting process. Excessive temperatures in operation can cause a shrinkage of 3 or 4 percent. Shrinkage may cause a bag to pull loose from its connection to the floor plate or the upper support structure.

Woven natural fabrics may be treated with flameproofing, moldproofing, shrinkproofing, and/or dust-releasing coatings, such as silicone to increase service life.[131] Woven synthetic fibers are often treated with flameproofing and dust-releasing coatings.

Woven fabric bags are made from cotton,

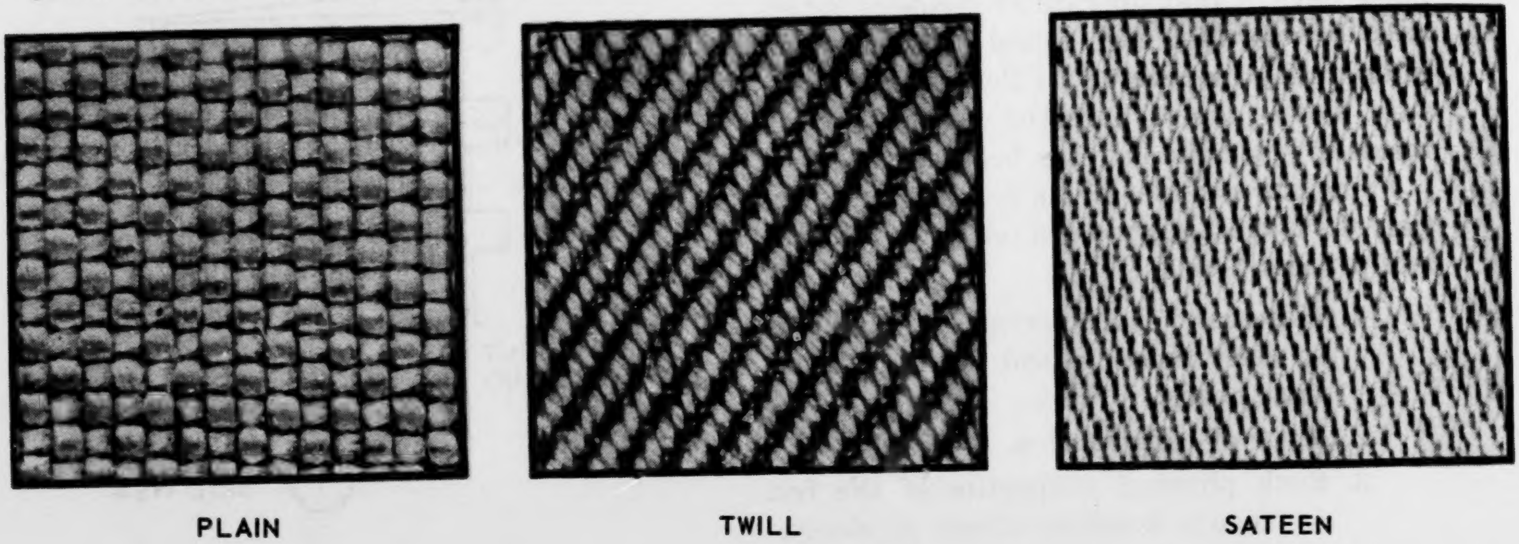

PLAIN TWILL SATEEN

Figure 4–74. Basic fabric weaves used for woven filter bags.
(Courtesy of West Point Pepperell, Industrial Fabrics Division)

wool, Dacron, Nylon, Orlon, Nomex, polypropylene, Teflon, and fiberglass.

Fiberglass fabric bags are treated with silicone, mixtures of silicone and colloidal graphite, and Teflon lubricants to provide protection against abrasion and flex failures caused by fiber-to-fiber rubbing.[150] These lubricants are effective at temperatures of from 100°F to 550°F.

Felted fabrics—Felted fabrics serve as filter media and are used in reverse jet and pulse jet baghouses with air-to-cloth ratios of 6:1 to 16:1,[126] or ratios 5 to 6 times [131] those woven fabric filters.

Felted bags are more expensive than woven bags. Wool is the only fiber that will produce a true felt. However, synthetic fibers can be needled to function as a felt filter fabric. Hence, felt is limited to wool and such synthetic fibers as Dacron, Nylon, Nomex, polypropylene, and Teflon. Cotton and fiberglass fibers do not make felted fabrics.

Felted fabrics are complex, labyrinthine masses of randomly oriented fine fibers. The relative thickness provides the advantages of maximum dust impingement and changes of direction of flow to entrap small dust and fume particles. Felted fabric filters operate with extremely high collection efficiencies.[151]

In some cases, felted bags do not function well in the collection of extremely fine fumes because the fine particles are embedded in the felt and are very difficult to remove in the cleaning cycle. In general, felted bags are cleaned by high-pressure reverse jet and jet pulse devices that operate at frequent intervals. In one unit, each felted bag is cleaned individually by reverse air flow from a pressure blower and a burst of compressed air released when the bag has been expanded.[151]

Principal considerations for proper selection of the most economical felt for a particulate process include: [150]

1. Necessary characteristics of the fiber to meet chemical and thermal resistance needs.
2. Type of construction.
3. Such physical properties of the felt as density, breaking strength, elongation, bursting strength, air permeability, and particle size retention.

4.7.4.4 Fabric Cleaning—Fabric flexing and reverse air flow through the cloth are two methods of cleaning collected particulate matter from fabric filters.

Fabric flexing—Manual shaking, mechanical shaking, and air shaking are three methods of fabric flexing used in cleaning filters. Air shaking is further broken into four methods: air bubbling, jet pulsing, reverse air flexing and sonic vibration.

Manual shaking is used in baghouses of about 500 to 600 square feet of cloth. A rap is transmitted to the framework from which the filtering bags are suspended. Vibration from the rap shakes the dust loose. Thorough cleaning is rarely achieved because the shaking action is dependent on the operator's vigor.[131] This method is the least expensive and least desirable.

Mechanical shaking (Figure 4-75) removes dust from woven fabrics in a manner similar to that achieved by hand shaking a rug.[126] The shaker mechanism provides a gentle but effective cleaning action on the bags without exerting undue stresses on the fabric.

The shaker design must allow for easy installation, alignment, and maintenance. Shaking is usually used for inside out filtering and is considered too vigorous for fiberglass bags unless special provisions are made for reducing the intensity of shaking.[145]

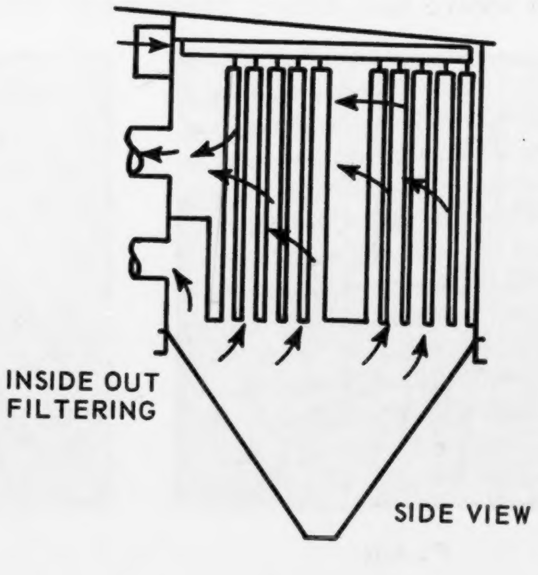


FIGURE 4-75. Mechanical shaking of bottom entry design uni-bag dust collector.

Air shaking (Figure 4–76) is done by flowing air between rows of bags, windwhipping the bags to make a dancing, cleaning action.[139] Bags are overcleaned near the orifice or jet and undercleaned in blind areas out of the windwhipping action. This method requires a minimum of hardware but is usually too vigorous for fiberglass bags.[145]

Air bubbling is done by releasing a traveling air bubble at the top of the bag during the cleaning cycle, as shown in Figure 4–77. The bubble travels down the bag during repressuring and causes it to ripple, thus cleaning the bag by shaking. The compressed air requirements are high and cleaning at higher air-to-cloth ratios has not been fully proven. This method is used for inside out filtering and sometimes for fiberglass bags.[145]

The jet pulse method employs a jet action of compressed air through a venturi section at the top of the bag (Figure 4–78). Smaller diameter tubular bags are held in place over a supporting screen, and dust is collected on the outside of an open-end-up tubular bag. Compressed air released at frequent intervals to a row of bags causes the bags to pulse outward, thus vibrating the fabric, and removing the dust. The dust is cleaned off by a flicking action on the collection surfaces rather than a reverse flow through the fabric. Felted fabrics usually are used with outside-in filtering. The jet pulse provides uniform pressure drop and continuous and automatic cleaning with no moving parts and permits higher air-to-cloth ratios, resulting in smaller units for equivalent capacity. The cost of a supporting frame and higher replacement costs of felted fabrics over woven fabrics are disadvantages of this method.[145]

Reverse air flexing is achieved by a double or triple cycle deflation of the bags followed by gentle inflating through low-pressure reverse flow, as shown in Figure 4–79. The cloth cleaning is not exclusively shaking, because some backwashing occurs. This method is used for inside out filtering with fiberglass bags.

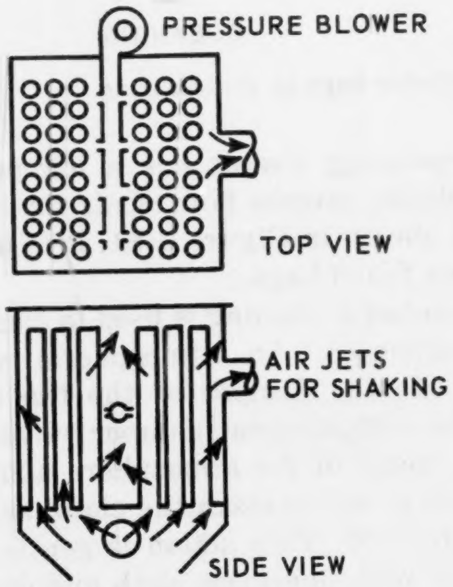


Figure 4–76. Air shaking wind-whip cleans dust collector bags.

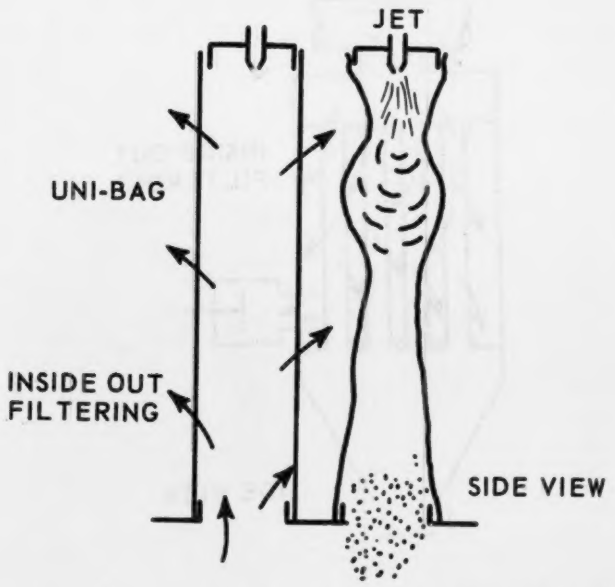


Figure 4–77. Bubble cleaning of dust collector bags.

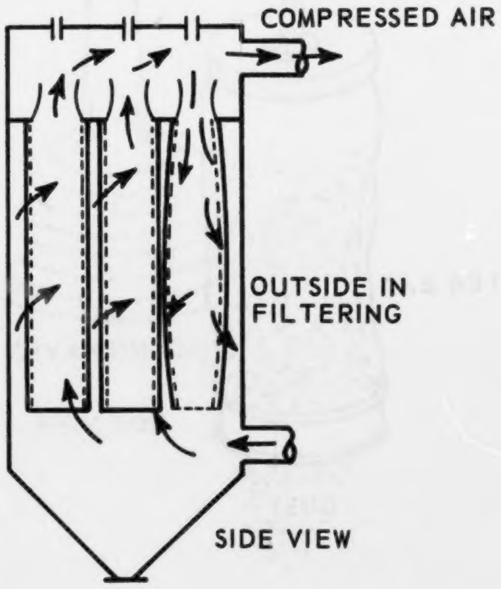


Figure 4–78. Jet pulse dust collector bag cleaning.

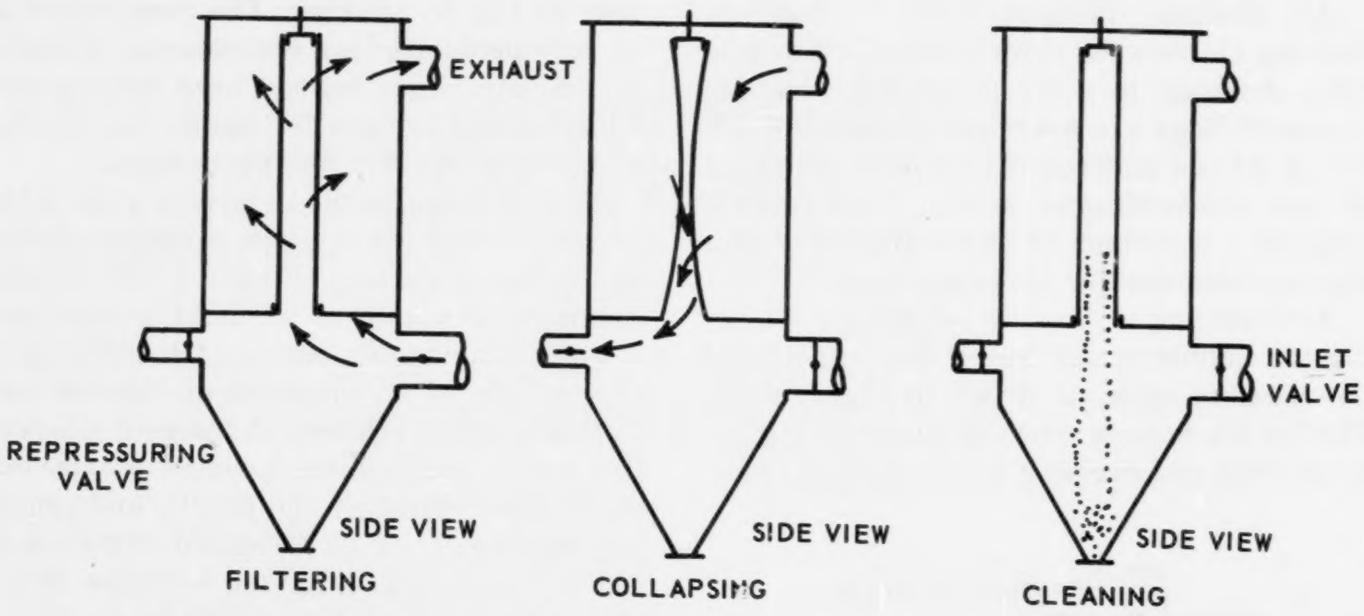

EXHAUST
REPRESSURING VALVE
SIDE VIEW
FILTERING
SIDE VIEW
COLLAPSING
INLET VALVE
SIDE VIEW
CLEANING

FIGURE 4-79. Reverse air flexing to clean dust collector bags by repressuring.

Occasionally, sonic generators are used to provide additional fabric vibrations for cleaning action.[145] Sonic generators vibrate the dust loose from the collecting fabrics as shown in Figure 4-80. They are sometimes used to supplement repressuring and reverse flow cleaning. Some carbon black and zinc oxide installations are using repressuring and sonic horns to clean fiberglass bags.[145]

Reverse air flow is divided into three methods: repressuring cleaning, atmospheric cleaning, atmospheric cleaning, and reverse jet cleaning.

Repressuring cleaning is a low-pressure, high-volume, reverse flow of air through the bags as shown in Figure 4-81. It is used for woven or felted bags.

Atmospheric cleaning is used in closed suction baghouses. An atmospheric vent is placed into the damper of the fan so that when the compartment damper valve closes, the vet opens to the atmosphere allowing a backwash of air to clean the cloth, as shown in Figure 4-82. This action is gentle and is only used with fiberglass cloth and easily removed dust. Sonic horns may be used to sup-

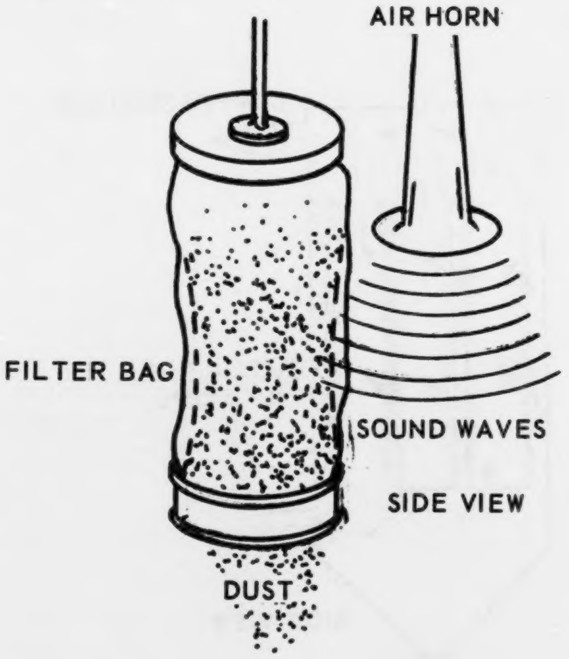

AIR HORN
FILTER BAG
SOUND WAVES
SIDE VIEW
DUST

FIGURE 4-80. Sonic cleaning of dust collector bags.

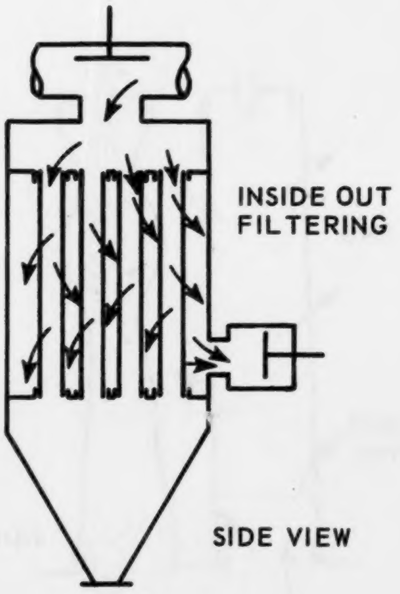

INSIDE OUT FILTERING
SIDE VIEW

FIGURE 4-81. Repressuring cleaning of dust collector bags.

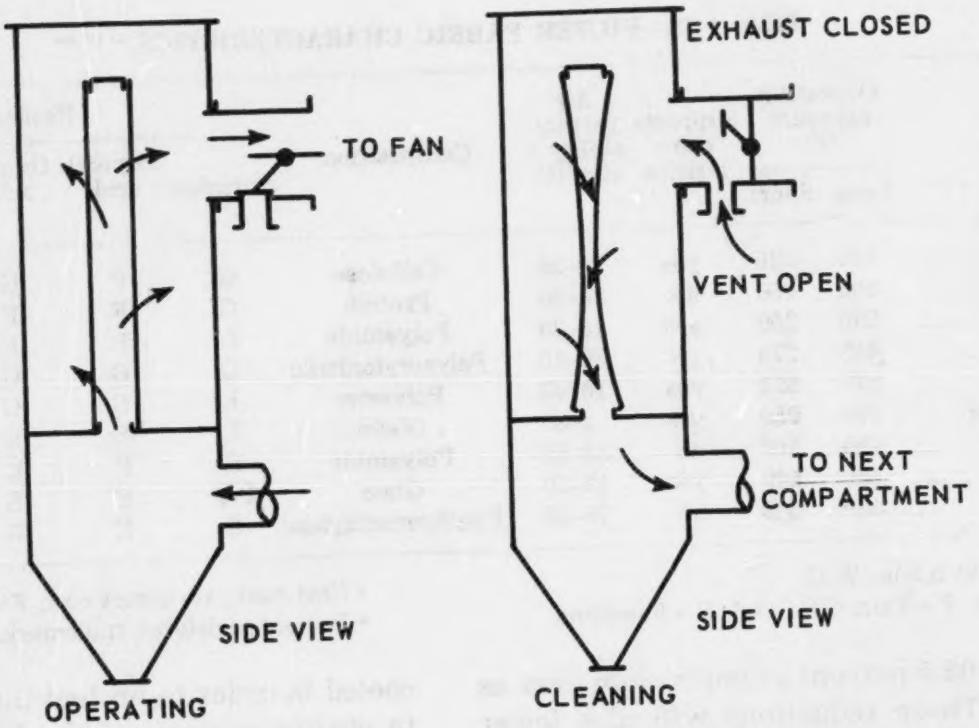


Figure 4–82. Cloth cleaning by reverse flow of ambient air.

plement the cleaning action. The amount of backwash air is dependent on cloth resistance. If the resistance is high the amount of backwash air is diminished, thus reducing the cleaning action.[145]

Reverse jet cleaning uses a traveling compressed air ring which moves up and down the outside of a tubular filter bag, thus blowing the dust back through the cloth and off the inside of the bag with compressed air as shown in Figure 4–83. Re-entrainment of fine dust during cloth cleaning has caused high pressure drops across some baghouses collecting fine fumes. The design is used successfully with felted bags with high air-to-cloth ratios collecting relatively coarse, nonabrasive dusts. The replacement costs of bags is somewhat high. The unit allows a compact installation.[145]

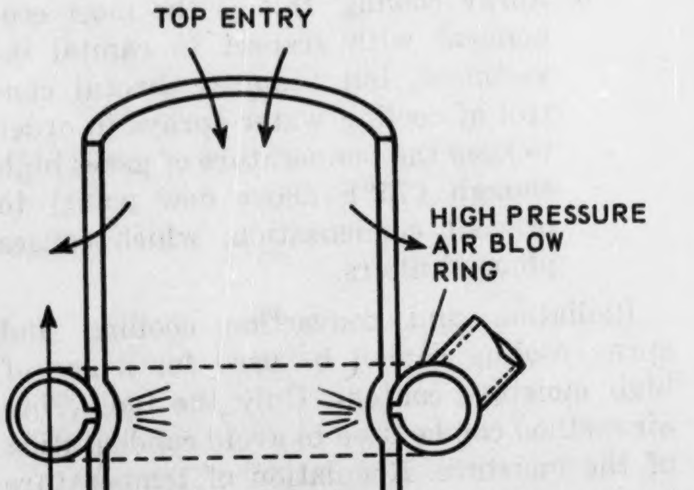


Figure 4–83. Reverse jet cleaning of dust collector bags.

The volume of air blown through the slot of the blow ring usually ranges from 1.0 to 1.5 cubic feet per minute per linear inch of slot.[131] Slot widths range from 0.03 to 0.25 inch.[152]

4.7.4.5 Fabric Selection—Fabrics that are presently applied in commercially available baghouses are shown in Table 4–13.[123, 147, 153] The finish applied to these fabrics is described in Section 4.7.4.3.

When comparing fabric cost ranks given in Table 4–13, other factors also should be considered. Use of a high-temperature fabric reduces the amount of dilution cooling required.[154] A high-temperature fabric requires less filtering area. For example, when cooling gases from 400°F to 250°F with ambient air at 90°F, the final gas volume is increased by 60 percent. The filter operating at 400°F re-

Table 4-13.—FILTER FABRIC CHARACTERISTICS [123] [147] [153]

Fiber	Operating exposure °F.		Supports combustion	Air permeability [a] cfm/ft²	Composition	Resistance [b]				Cost [c] rank
	Long	Short				Abrasion	Mineral acids	Organic acids	Alkali	
Cotton	180	225	yes	10–20	Cellulose	G	P	G	G	1
Wool	200	250	no	20–60	Protein	G	F	F	P	7
Nylon [d]	200	250	yes	15–30	Polyamide	E	P	F	G	2
Orlon [d]	240	275	yes	20–45	Polyacrylonitrile	G	G	G	F	3
Dacron [d]	275	325	yes	10–60	Polyester	E	G	G	G	4
Polypropylene	200	250	yes	7–30	Olefin	E	E	E	E	6
Nomex [d]	425	500	no	25–54	Polyamide	E	F	E	G	8
Fiberglass	550	600	yes	10–70	Glass	P-F	E	E	P	5
Teflon [d]	450	500	no	15–65	Polyfluoroethylene	F	E	E	E	9

[a] cfm/ft² at 0.5 in. W.G.

[b] P = Poor, F = Fair, G = Good, E = Excellent.

[c] Cost rank, 1 = lowest cost, 9 = highest cost.

[d] Dupont registered trademark.

quires only 62.5 percent as much cloth area as at 250°F. These reductions will also lower power costs for operating the filter.[154]

Fabric materials less commonly used are carbon, metals and ceramic fibers that will filter gases at temperatures up to 1600°F.[155] Beta fiberglass, a relatively new product, is more flexible than regular fiberglass and abrades less in service.[149]

4.7.4.6 Auxiliary Equipment—Auxiliary equipment that is selected during the original design includes dust handling equipment and precooling equipment.

Dust handling equipment—For collectors that are regularly cleaned and re-used, such dust handling equipment as hoppers must be provided for the collected dust. Hoppers empty through a dust gate, rotary lock or trickle valve into a screw or belt conveyor, a truck body, or a tote bin.[130] The dust is then conveyed to the final disposal point.

Careful consideration must be given to the dust handling system at the time the fabric collector is originally designed.[130] Failure to do so may result in leakage in the system that will redisperse the collected dust and create air pollution problems. Inaccessability of the handling equipment for servicing will make maintenance difficult. Undersizing of the dust disposal mechanism may block the upstream flow of process materials.

Precooling equipment—The application of cloth filtration to the cleaning of furnace gases in most cases requires that the gases be cooled in order to protect the filter fabric and to ensure economical bag life. The following three cooling methods are employed singly or in various combinations:[156]

1. Radiation and convection cooling, this requires a relatively large investment in U-tube coolers, or heat exchangers.
2. Admission of outside air for cooling, this results in relatively large filtration volumes with a resultant increase in the size of the gas cleaning equipment.
3. Spray cooling, this is the most economical with respect to capital investment, but requires careful control of cooling water sprays in order to keep the temperature of gases high enough (75°F above dew point) to prevent condensation, which causes plugged filters.

Radiation and convection cooling, and spray cooling cannot be used for a gas of high moisture content. Only the tempering air method can be used to avoid condensation of the moisture. Regulation of temperature is accomplished easily by this method. However, the outside air used for cooling also must pass through the filter, so the filter must be considerably larger than a filter used with U-tubes or spray cooling methods.

Spray cooling of hot gases is the least expensive method because the initial cost is reasonable, the maintenance is relatively easy, and the increase in gas volume to be filtered is nominal. However, careful control of cooling is needed to hold the temperature of hot gases 50°F to 75°F above the dew point.[145]

4.7.4.7 Individual Collectors Versus Large Collecting Systems—The individual fabric collector has several advantages over a large central collecting system in manufacturing plants where relatively few dust sources must be controlled.[157] The unit collector is self-contained, and has a lower erection cost because the unit is shipped erected, or nearly so, and because it can be installed at the point of need with minimum duct work. The unit collector's mobility is often economically important in a plant with idle batch processes where idle unit collectors may be moved to sites requiring dust control. The large central collecting system requires considerable floor space and is often erected outdoors. Outdoor erection of a central system may require insulation and even supplementary heat input to avoid chilling the gas to the dew point. The large central system is preferred in large manufacturing plants where many dust sources of continuous processes must be controlled.

4.7.5 Typical Applications

The following examples of fabric collector application are presented to show how they may be applied to control particulate matter from various sources. The use of fabric filters has been extended by the introduction of fiberglass bags capable of operations at temperatures up to 550°F. The use of synthetic fabric bags has resolved many problems associated with corrosive or moderate temperature dust emissions.

4.7.5.1 Cement Kilns—The collection of the dust from rotary cement kilns has long been a difficult problem. The difficulty arises from the large volumes of gas involved, the heavy loading of very fine particles, the high gas temperatures, and in the case of wet-process kilns, the presence of a large amount of water vapor.[158]

The conventional cyclone will collect a high percentage of the dust, but beyond this point the electrostatic precipitator is the only device besides the fabric collector capable of final and complete cleanup.[159–161] Efficiencies as high as 99.5 percent, outlet loadings below .02 grains per standard cubic foot, and plume opacities less than 10 percent have been reported for fabric filter applications to cement kilns.[160]

4.7.5.2 Foundary Cupolas—Emissions from a gray iron cupola are a prime example of particulate matter than can be controlled with high temperature fabric filtration. Cupola exhaust temperatures range from 1000° F to 2200° F with an average effluent loading of about 1 grain per cubic foot.[162] Much of the emission is fine metal oxide fume less than 0.5 micron in diameter. Gas cooling and high-temperature fabric filters are required. Evaporation cooling by water sprays is the most common technique used in gas cooling. Off-gas temperatures are reduced to about 450° F before filtration through fiberglass bags. In a typical installation the gas is filtered at rates of about 2.5 feet cfm/ft^2 through tubular bags that are 11½ inches in diameter and 15½ feet long. A bag life of one or two years can be expected if bags are used continuously. In noncontinuous service, averaging 20 to 40 on-stream hours per week, bags have been reported to last four or five years.[162]

4.7.5.3 Electric Arc Steel Furnaces—The electric arc steel furnace presents an emission control problem that is characterized by fine particulate matter containing a high percentage of oxides of iron, dispersed in a gas stream that is highly variable in temperature, loading, and volume during the different process cycles. Effluent volume is dependent on the type of hooding arrangement employed because the dilution air flow is adjusted to provide for gas cooling and in-plant dust control. Stack temperatures may reach 750° F or higher with closed, hooded units.[163]

The first large-scale fiberglass filter in the steel industry was installed in 1959 at a Seattle steel mill.[163] This unit handles 105,000 cfm at temperatures up to 500° F using fiberglass bags 11½ inches in diameter and 25 feet long that operate at an air-to-cloth ratio of 1.4. The fiberglass bags are cleaned by collapsing.

Another example is a furnace melting 45 tons of steel scrap in four hours and using an Orlon fabric filter to handle a volume of 60,000 cfm at 200°F. The bag replacement costs are approximately $1400 per year with a five year bag life.[163]

4.7.5.4 Open Hearth Furnaces—A major steel company conducted a study which found that iron oxide fumes generated by an oxygen-lanced open hearth furnace could be collected efficiently by fiberglass bags.[164]

The 10-compartment baghouse used in the study handles 145,000 cfm at 500° F, based on a filter ratio of 2 cfm/ft^2 when nine of the ten compartments are in operation. Each of the ten compartments contains 80 fiberglass bags, 11½ inches in diameter and 34 feet long (or 8070 square feet of filter surface per compartment). Reverse air flex cleaning, supplemented by sonic horns, is used. The efficiency of the baghouse is well over 99 percent under all conditions of inlet gas volume and dust loading. Inlet particulate loading has been as high as 20 grains per cubic foot during periodic cleaning of heat regenerative surfaces. The outlet dust loading has been measured at 0.007 grains per cubic foot.[165]

4.7.5.5 Nonferrous Metal Furnaces—One of the largest secondary lead smelters in the country has converted from synthetic fiber to fiberglass bags to permit fume collection at temperatures higher than 400° F. This installation cleans the combined effluent from a reverberatory furnace and a lead blast furnace. Higher filtering temperatures were desired in order to eliminate the deposition of organic tars on the bags. After 16 months' experience with fiberglass bags, operated at 1.2 cfm/ft^2 and cleaned by shaking, results are reported as satisfactory.[162]

After completion of pilot-scale studies with both synthetic and fiberglass media at an integrated smelter producing primary copper and zinc, a baghouse equipped with 222,000 square feet of fiberglass bags was constructed to clean the effluent streams from a reverberatory furnace and copper converters.[162] Fiberglass fabric was selected because of its corrosion resistance and because operation at 450° F reduced by 50 percent the radiation-convection heat transfer area that would have been required for cooling to temperatures safe for organic media. The average filter ratio is 1.6 cfm/ft^2. Bags 5 inches in diameter and 10 feet long are used. Bag cleaning involves collapse every half hour supplemented by mechanical shaking every eight hours. Sonic cleaning equipment has been tried experimentally. Based on present knowledge, an average bag life in excess of two years is anticipated.

4.7.5.6 Carbon Black Plants—Baghouses equipped with fiberglass bags are reported to be in use for the final cleaning in 35 of the 37 carbon black plants in the United States.[166] Earlier baghouses used synthetic bags and kept the filtration temperature below 250° F to protect the media. However, the temperature was regulated by evaporative cooling, which brought the gas stream close to the acid dewpoint and caused serious corrosion of fabric. The introduction of fiberglass in 1953 minimized this problem by allowing operation at temperatures of 400° F to 500° F. Bag collapse, with some supplementary vibration from sonic horns or other gentle means is the most common technique used for cleaning the fiberglass filters. Air-to-cloth ratios are usually 1.5:1. The average baghouse capacity is around 50,000 cfm, and bag life is 12 to 18 months.[166]

4.7.5.7 Grain Handling Operations—The important sources of grain dust emissions are cleaning, rolling, grinding, blending, and the loading of trucks, rail cars, and ships. Conveying and storing grains also cause dust emissions.

Low- and medium-efficiency cyclones only have been used because of the increased operating costs and maintenance problems associated with high-efficiency multiple cyclones. For grain dusts larger than 10 microns in diameter, medium-efficiency cyclones are satisfactory. For grain dusts smaller than 10 microns, the fabric filter is preferred.[167] Often, air streams containing large amounts of dust are passed through a cyclone to remove coarse particles before being directed to a fabric filter. This technique relieves the fabric filter from handling a high volume of large particles. Receiving, handling, and storing operations require hooding the emission source and conveying the dust-laden air to dust collection equipment. For receiving hoppers used in unloading rail cars and trucks, a method of control is to exhaust air from below the grating. The indraft velocity required will range from 100 to 300 feet per minute depending on whether the hopper is in a building or outside and exposed to winds.

The fabric filters with the open pressure or closed pressure baghouse with mechanically shaken woven cotton bags are reported to remove 99.9 percent of grain particles in the size range of 1 to 5 microns.[123] The air-to-cloth ratios are about 5:1.

Reverse jet filters which use felted fabrics are reported to remove 99.9 percent of grain particles in the size range of 1 to 5 microns with an air-to-cloth ratio as high as 15:1, although ratios of 12:1 are more common.[168]

4.7.6 Operational Practices

Operational practices are somewhat different for woven fabrics and felted fabrics. The bag life of woven fabrics is related to cleaning frequency. The more often a fabric, especially fiberglass, is cleaned, the shorter the bag life; this assumes that cleaning is conducted often enough to avoid fabric blinding by a dust overload. Fabric cleaning may be done when the pressure drop across the baghouse, or one of its compartments, increases to 6 inches of water.[131] In large baghouses, fabric cleaning is scheduled by compartment based on previous operating experience.

To avoid plugging of woven fabrics because of condensation, the gas temperature in the baghouse should be 50° F to 75° F higher than the dew point of the gas.[145] In some cases, insulated duct work and baghouses are needed to maintain gas temperatures. In some installations, a small auxiliary heater is used to prevent condensation in a baghouse when it is shut down.

The bag life of felted fabrics[131] is prolonged by reducing the frequency of cleaning. The cleaning cycle may be scheduled to hold the pressure drop across a reverse jet baghouse with felted bags to 3-5 inches of water.[169] Figure 4–48 illustrates the effect of pressure control on filter resistance in a reverse jet filter for dusts and fumes.[152]

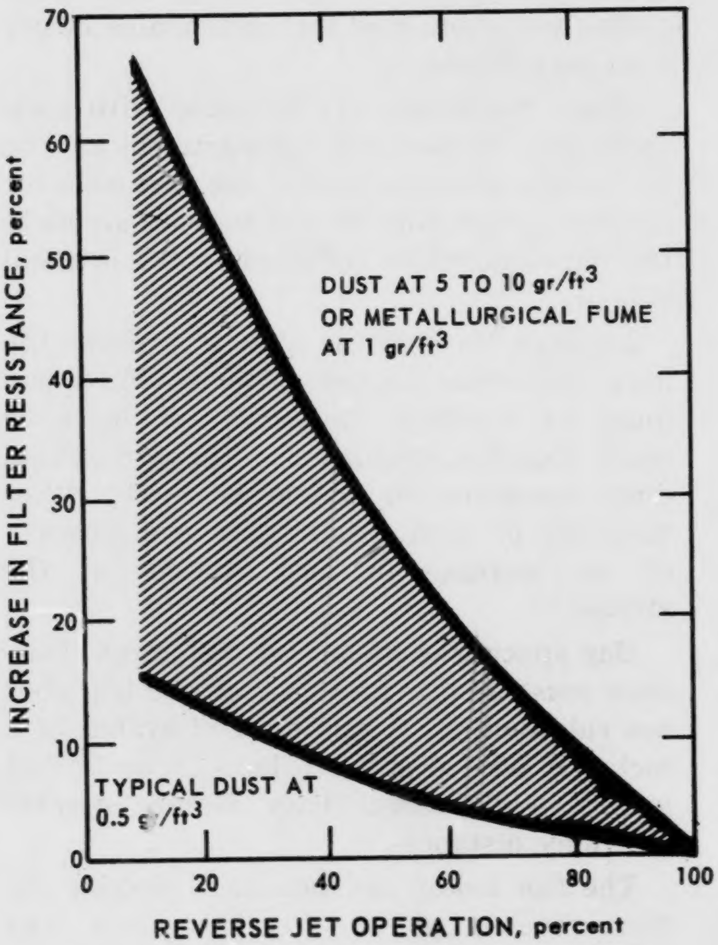


FIGURE 4–84. Effect of cleaning frequency on filter resistance in reverse-jet baghouse.
(Courtesy of Air Conditioning, Heating, and Ventilating magazine)

To avoid plugging of felted fabrics when handling gases with high moisture content, the use of preheated air for reverse jet cleaning may be necessary.[131]

4.7.7 Maintenance Procedures

Maintenance of a fabric collector is often related to adequacy of the original design. The installation of filters with high air-to-cloth ratios is often responsible for rapid replacement of bags. The replacement may be needed because of blinding of fabric or excessive bag wear.

An unusually heavy grain loading may cause excessive wear or blinding of a woven fabric. As a rule of thumb, particulate loadings above 10 grains per cubic foot are often handled by a precleaner such as a medium- or low-efficiency cyclone.[130] The cyclone will remove a large amount of particulate matter greater than10 microns in diameter. Reverse jet and pulse jet collectors can handle, without a precleaner, dust loadings up to 80 grains per cubic foot for particulates larger than 60 microns.[131]

Many baghouses are designed with compartments so that one compartment can be shut down while the rest of the dust collector continues operating. Means for easy access to the bags should be included in the original design.

Leakage through the filter is perhaps the most important service problem. Each bag must be regularly inspected for holes or tears. Regular measurement of down-stream dust concentration should be made either manually or with an electronic-eye, to warn of an increase in dust content of the stream.[141]

Bag spacing is important. Sufficient clearance must be provided so that one bag does not rub another. A minimum clearance of 2 inches is needed between bags 10 or 12 feet long,[131] while longer bags require greater clearance distances.

The fan motor and bearings, shaking device, reverse jet blow rings, valves, and dampers must be lubricated regularly and checked for wear.[130] To avoid extended downtime, worn parts should be replaced before they fail in service.

Regular inspection of ducts, hoods, framework, and housing for signs of wear from corrosion, erosion, excessive heat, and excessive moisture should be made.[130]

Pressure guages, thermocouples, flow meters, and all other instruments must be checked regulary to ensure that they are functioning accurately.[130]

A preventive maintenance program should be established and followed. Regular routine inspection of major lubricant locations is needed. The schedule may be altered to fit specific installations of dust collectors.[130]

4.7.8 Safety

Whenever dust is a combustible material, the principal hazard in the operation of fabric collectors is that of explosion and fire. Other hazards may arise in special cases, depending upon the toxicity or abrasiveness of the dust, i.e., human health hazards such as metal poisoning and silicosis. Continuous monitoring of discharge effluents is needed to avoid any mishaps.[130]

4.8 AFTERBURNERS

4.8.1 Introduction

Afterburners are gas cleaning devices which use a furnace for the combustion of gaseous and particulate matter. Combustion is accomplished either by direct flame incineration or by catalytic combustion.

The disposal of particulate matter by combustion is limited to residue-free vapors, mists, smoke, and particulate matter which is readily combustible, as well as to particle sizes which require short furnace retention time and small furnace size. Afterburners are usually used to dispose of fumes, vapors, and odors when relatively small volumes of gases and low concentrations of particulate matter are involved.

4.8.1.1 Definition of Terms—Direct flame combustion—The use of a separately-fired burner in direct flame contact with the particle-laden gas to sustain rapid oxidation. Heat transfer occurs by conduction, convection, and radiation.

Catalytic combustion—A method of oxidizing combustible gases and vapors on the surface of a catalyst, without flame and at a lower temperature than corresponding flame temperatures.

Catalyst—A substance which increases the combustion rate and theoretically is unchanged by the combustion process.

Flash point temperature—The lowest temperature at which the vapors above a volatile combustible substance ignite momentarily in air, tested usually by applying a small flame under specific test conditions. Flash point temperatures are dependent on the geometry of the vapor-filled space, and differ from open and closed containers.

Auto-ignition temperature—The lowest temperature at which a volatile flammable substance will ignite and sustain combustion.[170]

4.8.1.2 Advantages and Disadvantages of Afterburners—The advantages and disadvantages of direct flame and catalytic afterburners are cited to allow a comparison to be made of the two types of gas cleaning devices.

Direct flame—Advantages of the direct flame incineration afterburner include: (1) high removal efficiency of submicron odor-causing particulate matter, (2) simultaneous disposal of combustible gaseous and particulate matter, (3) compatibility with existing combustion equipment, (4) relatively small space requirements, (5) simple construction, (6) and low maintenance.

Disadvantages include: (1) high operational costs including fuel and instrumentation, (2) fire hazards, and (3) excessive weight.

Catalytic—Advantages of the catalytic afterburner include: (1) reduced fuel requirements, (2) and reduced temperature, insulation requirements, and fire hazards.

Disadvantages include: (1) high initial cost, (2) sensitivity to catalytic poisoning, (3) inorganic particles must be removed and organic droplets must be vaporized before combustion to prevent damage and plugging of the catalyst, (4) catalysts may require frequent reactivation, and (5) lower efficiency at the usual catalytic afterburner operation temperature.

Catalytic afterburners frequently require a direct flame air preheater to initiate and sustain catalytic combustion, thereby further reducing the relative advantage of the catalytic afterburner. Methane from the incomplete combustion of the direct flame preheater fuel is not oxidized at low temperature in the catalyst bed. Incomplete combustion and the formation of oxygenated compounds may be prevented by operating the catalyst bed at elevated temperatures with a consequent reduction in the thermal advantage and fuel savings over direct flame combustion.

Catalytic afterburners frequently are unable to meet the local code requirements as to combustion efficiency at the usual catalytic afterburner operating temperature.[*]

4.8.1.3 Combustion Theory—Cumbustion is the chemical reaction of a fuel with an oxidant, involving the disappearance of the original reactants and the production of heat and oxides. Combustion usually takes place in a thin reaction zone.

When solid fuels burn, the reaction zone is confined to the surface of the particle. At low temperatures the combustion rate is limited by the chemical reaction rate, whereas at higher temperatures the chemical-reaction rate is so rapid that the rate of air supply controls the combustion rate.[171, 172]

Combustion of liquid droplets and volatile solids occurs away from the surface of the particle and combustion rate may be dependent on the rate of heat transfer to the surface, which causes evaporation and thermal decomposition of the solid. Combustion is influenced by the gas velocity, the rate of mixing, and the supply of oxygen.[173, 174]

The temperature in the combustion zone surrounding the particulate matter may exceed the temperature at the interior of the particle and in the surrounding gas by several hundred degrees. Heat transfer is largely by radiation from the incandescent surface of the particle, or from the incandescent carbon formed as an intermediate step in the combustion process.[175]

Catalytic combustion—The mechanism of surface catalysis is very complex. The catalytic combustion process occurring on the surface of the catalyst involves diffusion of the reacting molecules to the surface of the catalyst through a stagnant gas film which surrounds the surface of the catalyst, adsorption of the reactants on the surface, chemical combination of the reactants, desorption of the combustion products, and diffusion of the combustion products from the surface of the catalyst to the main gas stream. The rate of catalytic oxidation is usually controlled by adsorption, chemical combination, desorption, or a combination of these.[176]

Catalytic combustion occurs at a lower temperature than direct flame oxidation by substituting catalytic adsorption energy for thermal energy of activation (energy necessary for chemical combination) and by increasing the concentration of the reactants on the surface of the catalyst.

The chemical union of the oxygen with the organic compounds occurs without flame on the surface of the catalyst, with the transfer of the heat of combustion from the catalytic bed to the gas stream.

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[*] Los Angeles County Rule No. 66: 90 percent or more of the carbon in the organic material being incinerated must be oxidized to carbon dioxide.

Many substances exhibit catalytic properties, but metals in the platinum family are recognized for their ability to produce combustion at minimum temperatures. Because catalysis is a surface phenomenon, relatively small amounts of metal are used and supported to expose a maximum of surface area. Other catalysts include copper chromite, and the oxides of copper, chromium, vanadium, manganese, nickel, and cobalt.[176, 177]

Catalysts may be subject to poisoning from such materials as zinc, arsenic, lead, mercury, copper, iron, antimony, and phosphates. Other materials which commonly suppress catalysis include halogen, and sulfur compounds.[178, 179] Poisoned catalysts may be reactivated by periodically washing the catalyst with acid solutions.

4.8.2 Afterburner Design Criteria

4.8.2.1 General—Variables which must be considered in the selection and/or design of afterburners for particle-containing gaseous wastes are heat transfer, reaction temperature, particulate size, mixing, flame contact, residence time, inlet gas temperatures, and composition. The variables are interdependent and, as a consequence, design criteria are semi-empirical because of the large range of materials dealt with, the lack of design data, and the relatively loose control of operating conditions.

4.8.2.2 Heat Transfer—The transfer of heat from burner flame to gaseous and particulate matter is an important factor in determining the furnace size, operating temperatures, and fuel requirements of direct flame contact incinerators. Heat transfer is best achieved by mixing when gases are burned, and best achieved by radiant heat transfer when particulate matter is burned.[180, 181]

For purposes of burning particulate matter, radiant heat transfer and furnace temperature uniformity may be increased by increasing the emissivity of the burner flame. This can be accomplished by limiting the air supply to produce a sooty flame, by using high carbon-to-hydrogen ratio (C/H) fuels, by adding soot or fuel oil (by carburetion) to gas flames, by using low-velocity burners, through poor mixing of air and fuel, and by altering furnace design.[182–184]

4.8.2.3 Reaction Temperature—Most direct flame burners operate in the 1200° to 1500° F temperature range in order to obtain maximum combustion within the limits of flame contact, mixing, and residence time in the furnace.[185]

Figure 4-85 illustrates the effect of air velocity and particle diameter on the combustion rate of carbon.[186–188] The effects of particle size, reaction temperature, combustion gas composition, and gas velocity on the combustion rate of carbon, coal, and a number of other compounds have been investigated.[171–174, 189–191]

Adsorption catalysts are used in fume burners operated in the 800°F to 1200°F temperature range. Furnace and catalyst temperatures, space, velocity, and bed depth

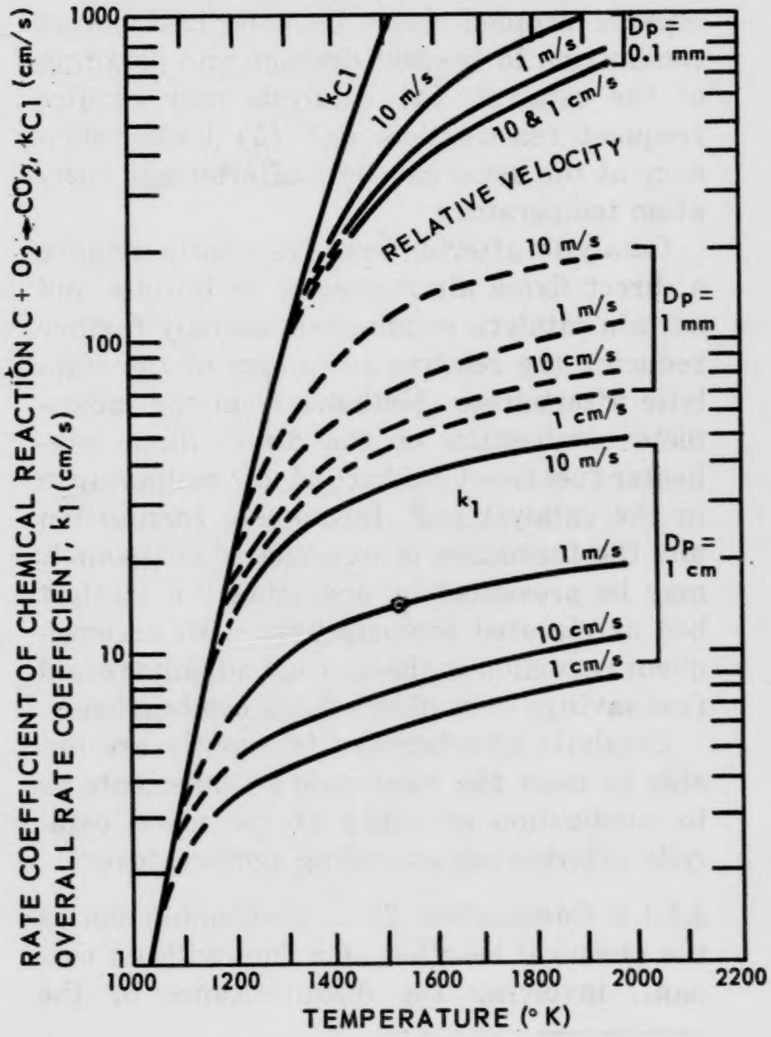

FIGURE 4-85. Effect of air velocity and particle diameter on the combustion rate of carbon. (D_p= particle diameter)

are used to achieve the desired level of combustion efficiency (Figures 4-86 and 4-87).[192–194]

Compounds such as methane, which are difficult to oxidize, require a catalytic bed temperature approximately 200° F higher than ethane, propane, butane, and other members of the paraffin series.[195] Carbon monoxide, which is difficult to oxidize by direct flame combustion at low temperatures, is easily oxidized by platinum at a temperature of approximately 300° F and by hopcalite catalysts at room temperature.[176, 196]

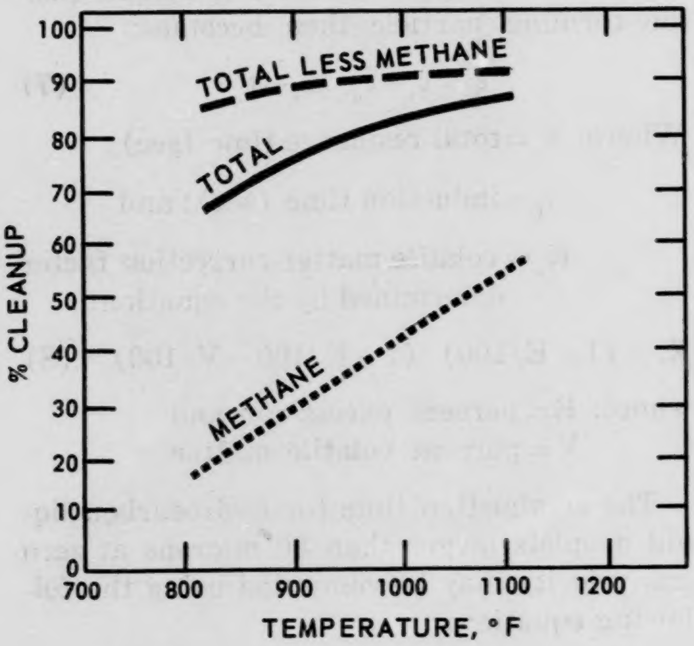

FIGURE 4-86. Combustion efficiency of catalytic afterburner.

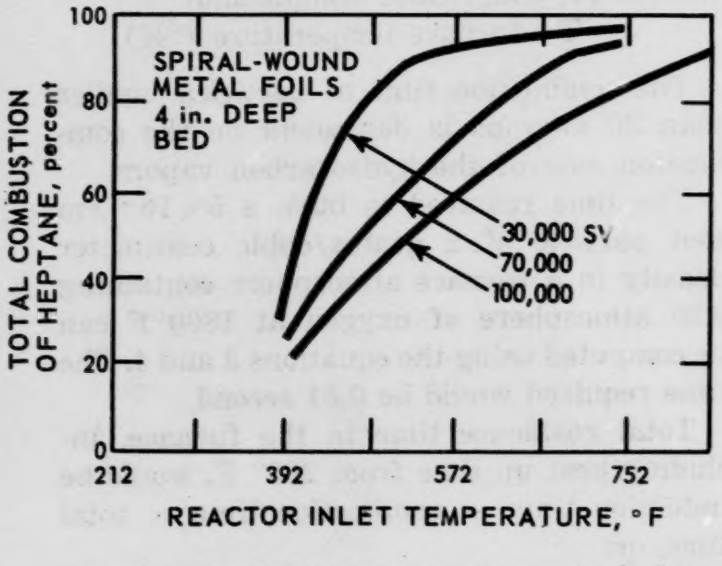

FIGURE 4-87. Effect of temperature and velocity on abatement effectiveness: spiral-wound metal foils catalyst support.

(Courtesy of the Journal of the Air Pollution Control Association)

4.8.2.4 Retention Time—Pre-heat (induction) and combustion times will dictate the overall residence time of the particulate matter in the afterburner. Residence time requirement will determine both combustion chamber dimensions and efficiency.

The time required to heat the waste gas to peak furnace temperature is dependent on the burner combustion chamber dimensions and efficiency.

The time required to heat the waste gas to peak furnace temperature is dependent on the burner combustion intensity and inlet gas temperature and may be computed as follows:

$$\text{heat up time (seconds)} = \frac{\text{heat capac. of gas (Btu/ft}^3\text{-°F)} \times \text{temp. rise (°F)}}{\text{combustion intensity (Btu/ft}^3\text{-sec)}} \quad (1)$$

Values of combustion intensity will vary from 1 Btu per cubic foot per second for low-pressure gas jet mixers to 500 Btu per cubic foot per second for premix mechanical burners. A typical value is 140 Btu per cubic foot per second for premix high-pressure gas jet multiple-port burners.

The time required to heat a gas with a heat capacity of 0.0182 Btu/ft^3-°F, from 200° F to 1800° F in a furnace with a combustion intensity of 140 Btu per cubic foot per second would be:

$$\text{Time (seconds)} = 0.0182 \times (1800 - 200)/140 = 0.208 \text{ seconds}$$

Combustion time required is dependent on particle size, oxygen content of the furnace atmosphere, furnace temperature, particle composition, gas velocity, and mixing of combustibles. Combustion times for a number of different materials have been determined and correlated on the basis of the following equations:[196]

$t_d = \rho R' T_m x_o^2 / (96 \phi D p_g)$ for diffusion-controlled combustion rate (2)

$t_c = \rho x_o / (2 K_s p_g)$ for chemical reaction-controlled cumbustion rate (3)

Where: t_d = diffusion-controlled combustion time (seconds);

t_c = chemical reaction rate-controlled combustion time (seconds);

ρ = density of carbon residue or coke (gm/cm^3);

R' = universal gas law constant (82.06 atm cm^3/mole/°K);

T_m = mean temperature of stagnant gas film (°K);

x_o = original diameter of particle (cm);

ϕ = combustion mechanism = 1 for CO and 2 for CO_2 formation;

D = diffusion coefficient of oxygen at temperature T_m (gm/cm^2);

p_g = partial pressure of oxygen in combustion air (atm); and

K_s = surface reaction rate coefficient (gm/cm^2 sec atm).

K_s may be calculated by means of the follow- equations:

$$K_s = 1.085 \times 10^4 \times T_s^{-1/2} \times e^{-39,300/RT_s} \text{ (for soot)} \quad (4)$$

$$K_s = 8710 \times e^{-35,700/RT_s} \text{ (for coke and carbon residue)} \quad (5)$$

Where: T_s = surface temperature of the carbon.

Equation 2 holds at high temperature, zero gas velocity, and large particle sizes. The equation can be corrected for the effects of gas velocity and turbulence by use of the dimensionless Nusselt conventional heat transfer relationship for spherical particles:[181]

$$N_{Nu} = 2 + 0.68\, N_{Pr}^{1/3} \times N_{Re}^{1/2}$$

Where: N_{Nu} = Nusselt Number;

N_{Pr} = Prandtl Number, a function of the physical properties of the gas; and

N_{Re} = Reynolds Number, a function of the physical properties of the gas, particle diameter, and gas velocity.

The Nusselt Number $N_{Nu} = h\, x/k = 2$ at zero gas velocity where: h = convectional heat transfer coefficient (cal/cm^2 °C sec); x = particle diameter (cm). h is an inverse function of the stagnant gas film thickness, x/2, surrounding the particle and directly proportional to the thermal conductivity of the furnace atmosphere, k (cal/cm^2 °C cm sec).

The film thickness decreases with increasing velocity and decreasing particle size to such an extent that the combustion rate for particles smaller than 100 microns is limited only by chemical kinetics at normal afterburner temperatures.

Equation 2 is of limited value in afterburner design because particles larger than 100 microns are easily collected by other gas cleaning devices and would require excessive retention time and furnace volume.

Equation 3 holds for particle sizes smaller than 100 microns and for temperatures at which the combustion rate is determined by chemical kinetics.

Total combustion time for a carbon residue-forming particle then becomes:

$$t_r = t_i + t_d \cdot K_v + t_c \quad (7)$$

Where: t_r = total residence time (sec);

t_i = induction time (sec); and

K_v = volatile matter correction factor determined by the equation:

$$K_v = (1 + E/100)/(1 + E/100 - V/100) \quad (8)$$

where: E = percent excess air and
V = percent volatile matter

The combustion time for hydrocarbon liquid droplets larger than 30 microns at zero gas velocity may be computed using the following equation:[188]

$$t_d = (29,800/p_g)\ M_w\ T^{-1.75} \cdot x_o^2 \quad (9)$$

Where: M_w = molecular weight and
T = furnace temperature (°K)

The combustion time of particles smaller than 30 microns is dependent on the combustion rate of the hydrocarbon vapors.

The time required to burn a 5×10^{-6} cm soot particle of 2 grams/cubic centimeter density in a furnace atmosphere containing 0.20 atmosphere of oxygen at 1800°F can be computed using the equations 3 and 4. The time required would be 0.51 second.

Total residence time in the furnace, including heat up time from 200° F, would be induction time + combustion time = total time, or:

$$t_r = 0.208 + 0.510 = 0.718 \text{ second}$$

In practice, minimum gas furnace retention time is about 0.30 second at a temperature of 1200°F. Particle retention time may be increased by designing the combustion chamber in the shape of a cyclone using a small tangential inlet, and by introducing the gases at a high velocity (Figure 4–88).[185]

Cyclone furnace dimensions are chosen using a gas velocity of from 15 to 30 feet per second.[185, 194] Good mixing is attained by using appropriate design parameters to provide turbulent flow in the afterburner.

A tangentially fired, portable hood, smoke afterburner is shown in Figure 4–89.

The combustion constants for a number of organic compounds are presented in references 171 through 175, 186 through 191, and 195 through 197.

4.8.2.5 Heat Recovery—Inlet waste gas temperatures should be as high as possible to minimize additional fuel and preheat requirements.[198–201] The maximum recoverable energy in afterburner stack gases as a function of exhaust gas temperature is shown in Figure 4–90, with waste gas energy content and temperature as parameters.

Heat recovery equipment used to recover heat from the flue gas may be grouped under two classifications: recuperative and regenerative. Recuperative (recovery) heat exchangers recover heat on a continuous basis and include cross flow, countercurrent flow, and cocurrent flow heat exchangers (Figures 4–91 through 4–93). For a given heat flow and temperature drop, heat exchanger surface requirements will be at a minimum in the counterflow heat exchanger (Figure 4–91).[202]

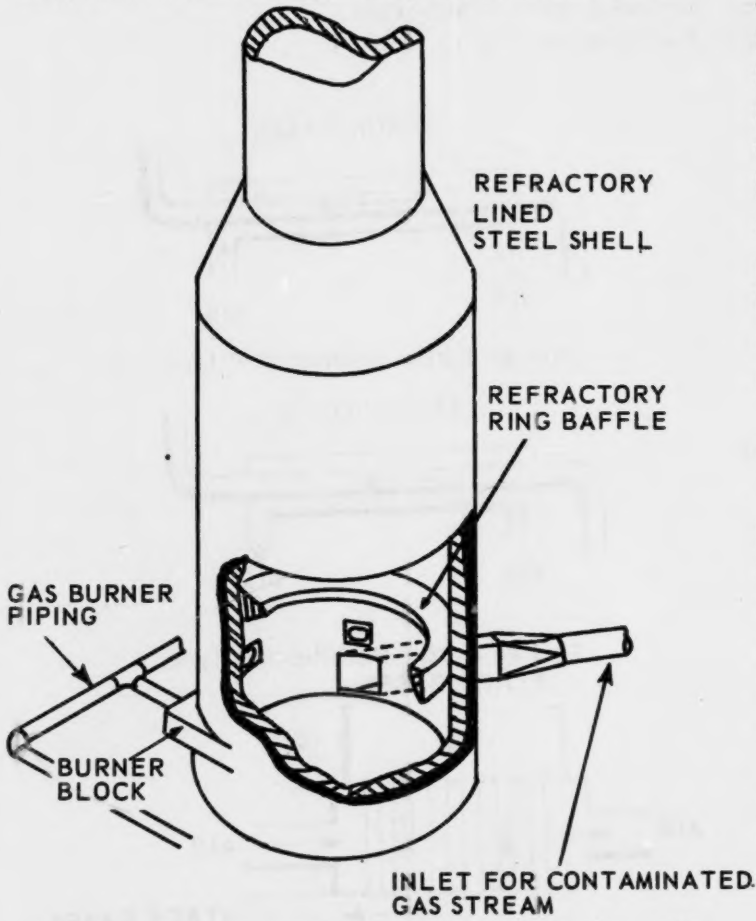

FIGURE 4–88. Typical direct-fired afterburner with tangential entries for both fuel and contaminated gases.

Cocurrent flow heat exchangers are often used where a moderate level of heat recovery is required. Countercurrent flow heat exchanger construction may be more costly than that for cocurrent flow, because of operation at lower temperatures (near the dewpoint), which may require use of special alloys or alloy steels.

Regenerative heat exchangers recover heat by intermittent heat exchange by the alternate heating and cooling of a solid. Heat flows alternately into and out of the same exchanger, as air and flue gas flow are periodically reversed. Regenerative heat exchangers are of fixed and moving bed types.

A fixed-bed, pebble-stove, regenerative afterburner is shown in Figure 4–94. When gas is passed through the pair of pebble-type regenerators connected back to back, the gas is heated on the upstream side and cooled on the downstream side. When the upstream bed and gas temperature drop, gas flow is reversed and the heat transfer process is repeated. Particulate matter is effectively retained and incinerated. Heat recovery efficinecies in excess of 95 percent can be achieved.[203]

A commonly used rotary regenerative heat exchanger consists of a partitioned rotating cylinder containing heat sink and heat transfer surface area. The cylinder is partitioned along its axis by appropriate gas seals so that hot flue gas and cold waste gas may be passed through the heat exchanger on opposite sides of the cylinder. Heat is absorbed from the hot flue gas by the heat exchanger surface and transferred by the continuous rotation of the heat exchange surface to the cold waste gas side where the heat is absorbed by the incoming cold gases. Heat recovery efficiency ranges from 85 to 95 percent.[203]

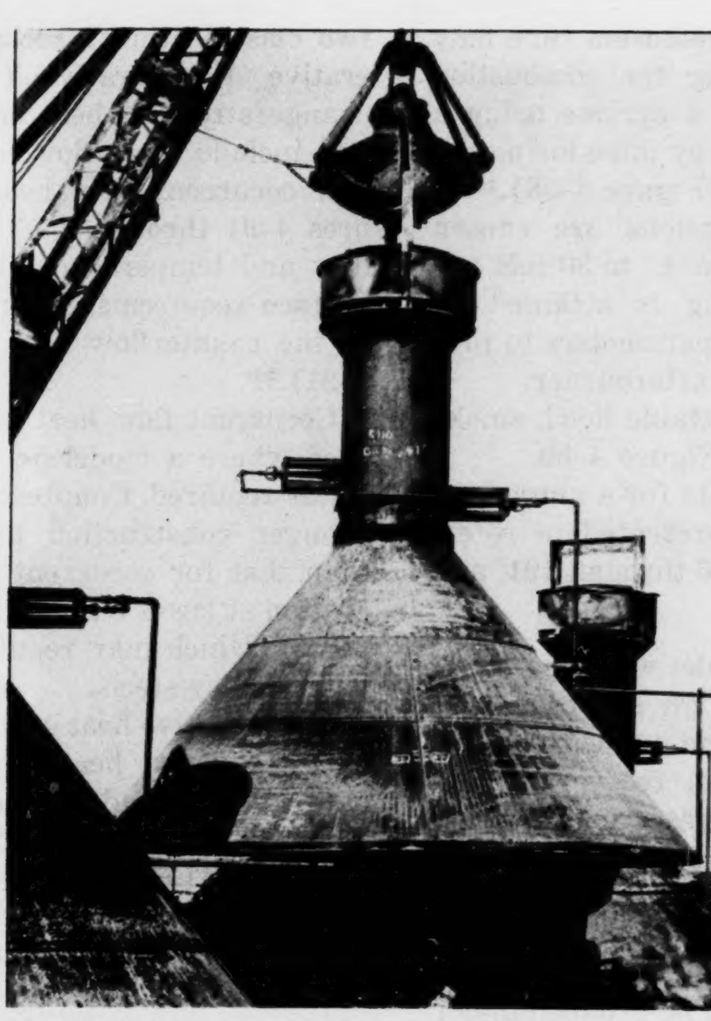

FIGURE 4-89. Portable canopy hood with stack afterburner. (*Courtesy of Eclipse Fuel Engineering Company*)

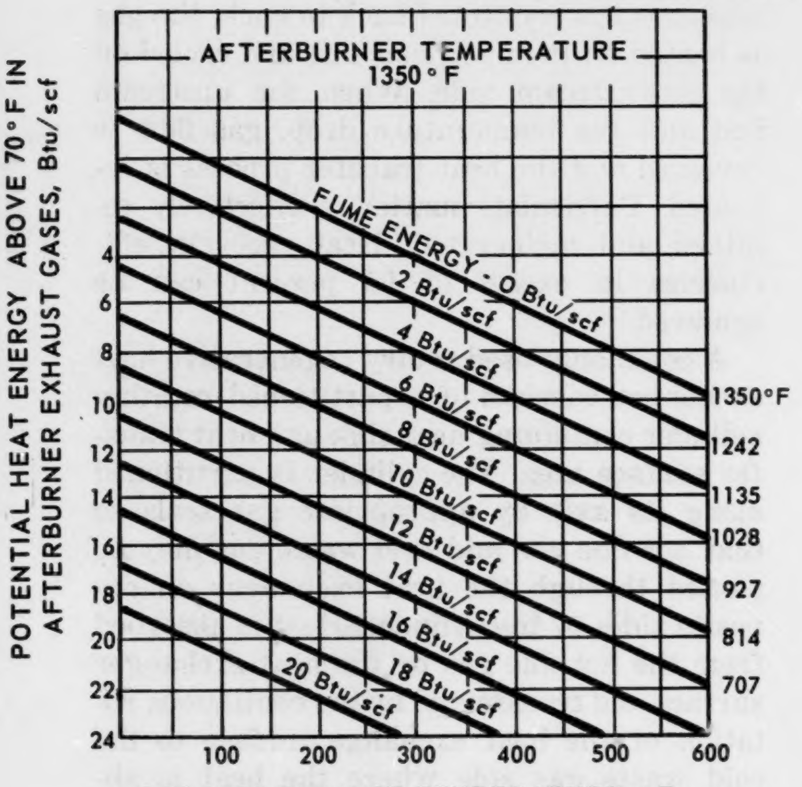

FIGURE 4-90. Afterburner energy requirements with fume energy content and temperature parameters.

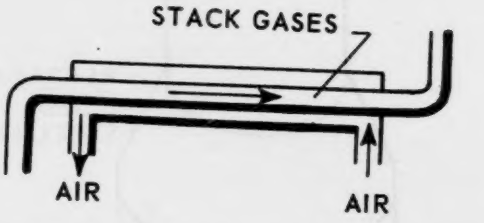
STACK GASES
AIR
AIR

FIGURE 4-91. Counter-flow type.

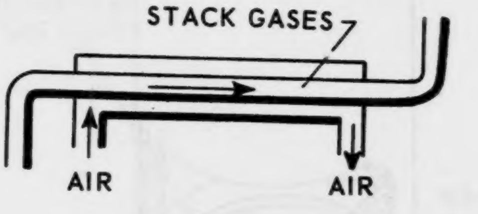
STACK GASES
AIR
AIR

FIGURE 4-92. Parallel-flow type.

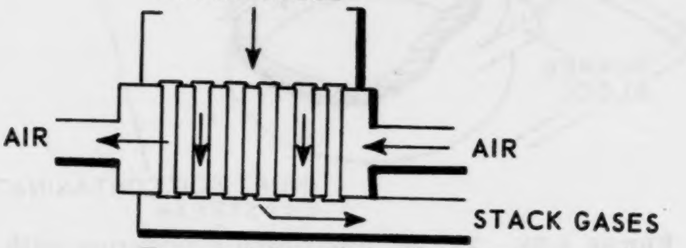
STACK GASES
AIR
AIR
STACK GASES

FIGURE 4-93. Cross-flow type.

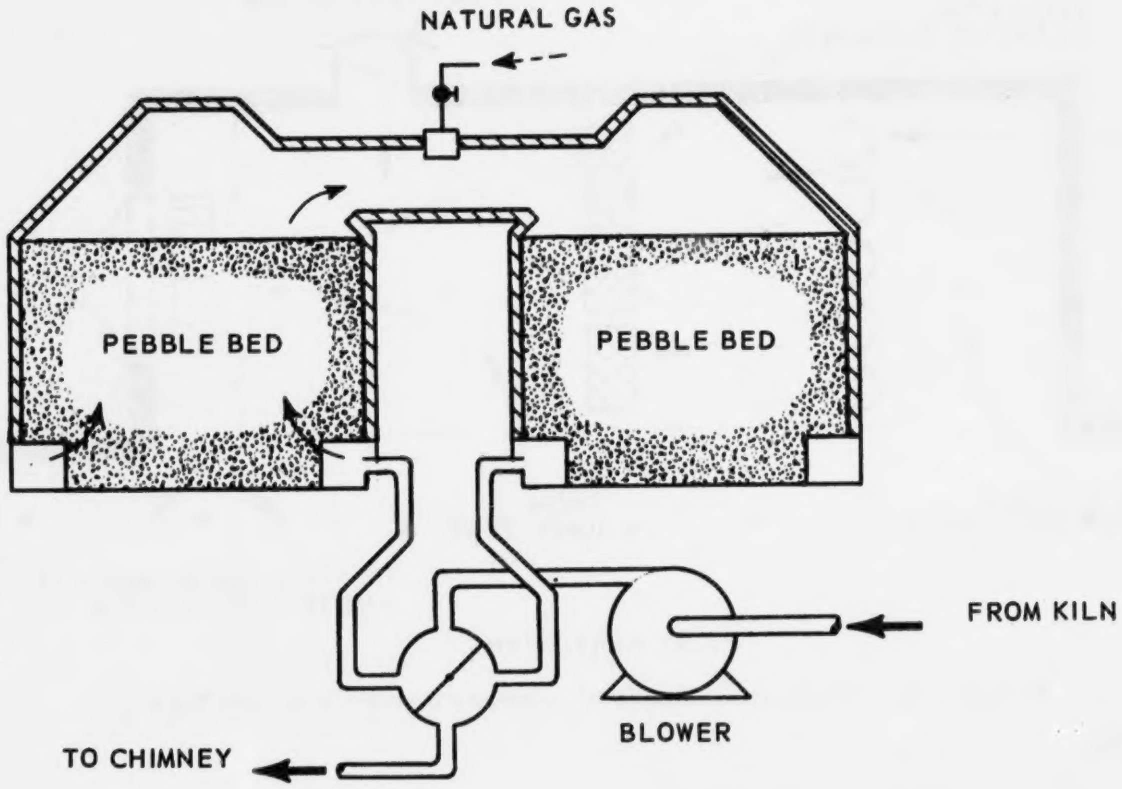

FIGURE 4–94. Fixed-bed, pebble-stone, regenerative destencher.
(Courtesy of Research Cottrell)

4.8.2.6 Fuel Requirements—Maximum fuel consumption for one-pass catalytic afterburners may be as high as 10 Btu per standard cubic foot of waste gas flow, while systems with heat exchangers can economically reduce heat requirements to about 4 Btu per standard cubic foot.[199] The heating value of the waste gas stream is usually limited by insurance underwriters to combustible vapor concentrations of less than one-fourth of the lower explosive limits of the gas mixture. For organics, this is equivalent to about 13 Btu per standard cubic foot and represents a total temperature rise of approximately 675° F, equivalent to 52° F to 55° F per Btu per standard cubic foot. Catalytic combustors are usually equipped with automatic safety controls when treating high organic concentrations.

The heat generated by the combustion of solvent and paint fumes may be directly recovered by recirculating the combustion gases to the oven (Figure 4–95), or indirectly recovered by means of heat exchangers (Figure 4–96). Direct heat recovery may be advantageous in the case of catalytic combustion because of lower oxygen requirements in the catalytic combustion zone.[204, 205] This can be advantageous with materials having a low explosive limit.

Fuel savings from the use of the heats of combustion of paint bake-oven solvent vapors may be large enough to provide a 50 percent return on investment in the case of catalytic combustion.[204]

Fuel requirements and burner capacity may be determined by means of a heat balance, using the heat of combustion of the fuel and the sensible heat needed to raise the temperature of the waste gas and the products of combustion up to the desired combustion temperature. The heating value of the contaminant must be deducted to determine net fuel requirements.[185, 205–208]

4.8.2.7 Modified Furnace Afterburners—Existing boilers, rotary kilns, and furnaces have been successfully modified and used for direct flame incineration. Requirements for successful operation are:

1. Contaminants must be combustible and non-corrosive.
2. The oxygen content of the contaminated gas must be high, or of such volume that it does not upset or reduce furnace capacity.

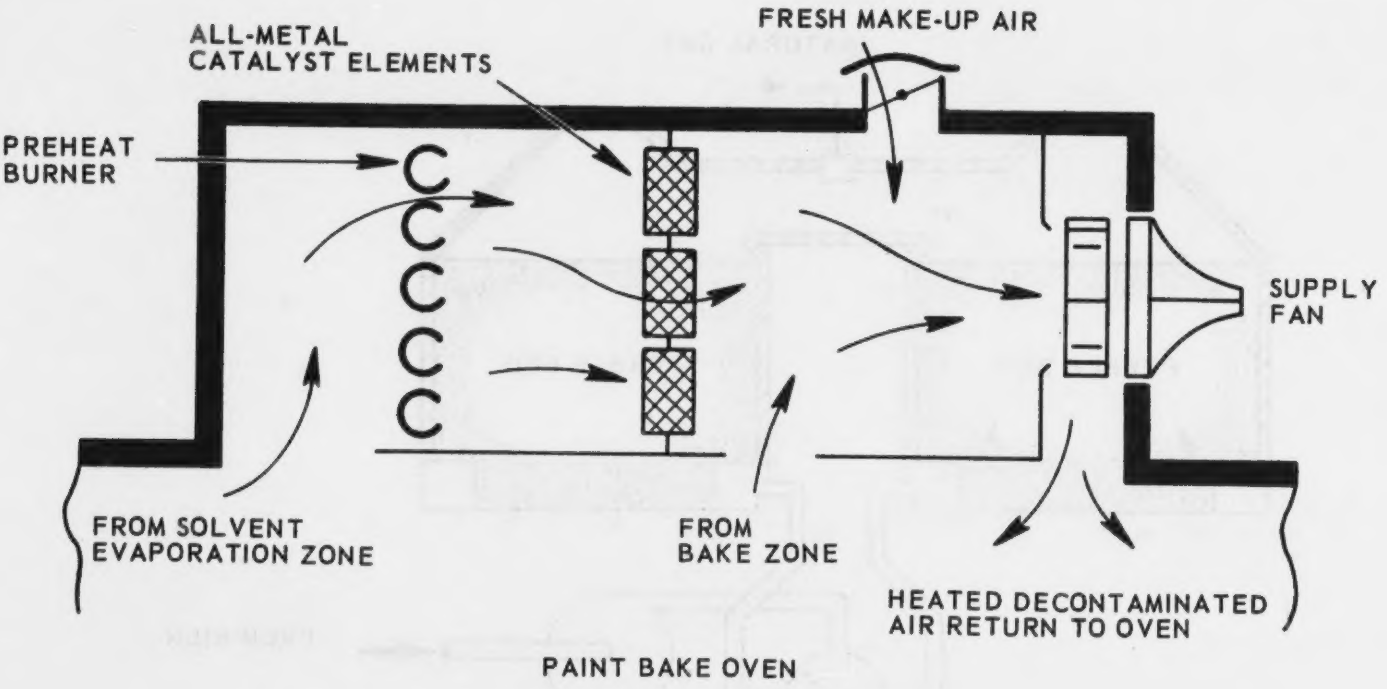
ALL-METAL
CATALYST ELEMENTS
FRESH MAKE-UP AIR
PREHEAT
BURNER
SUPPLY
FAN
FROM SOLVENT
EVAPORATION ZONE
FROM
BAKE ZONE
HEATED DECONTAMINATED
AIR RETURN TO OVEN
PAINT BAKE OVEN

FIGURE 4–95. Direct recirculation of combustion gases to recover heat.

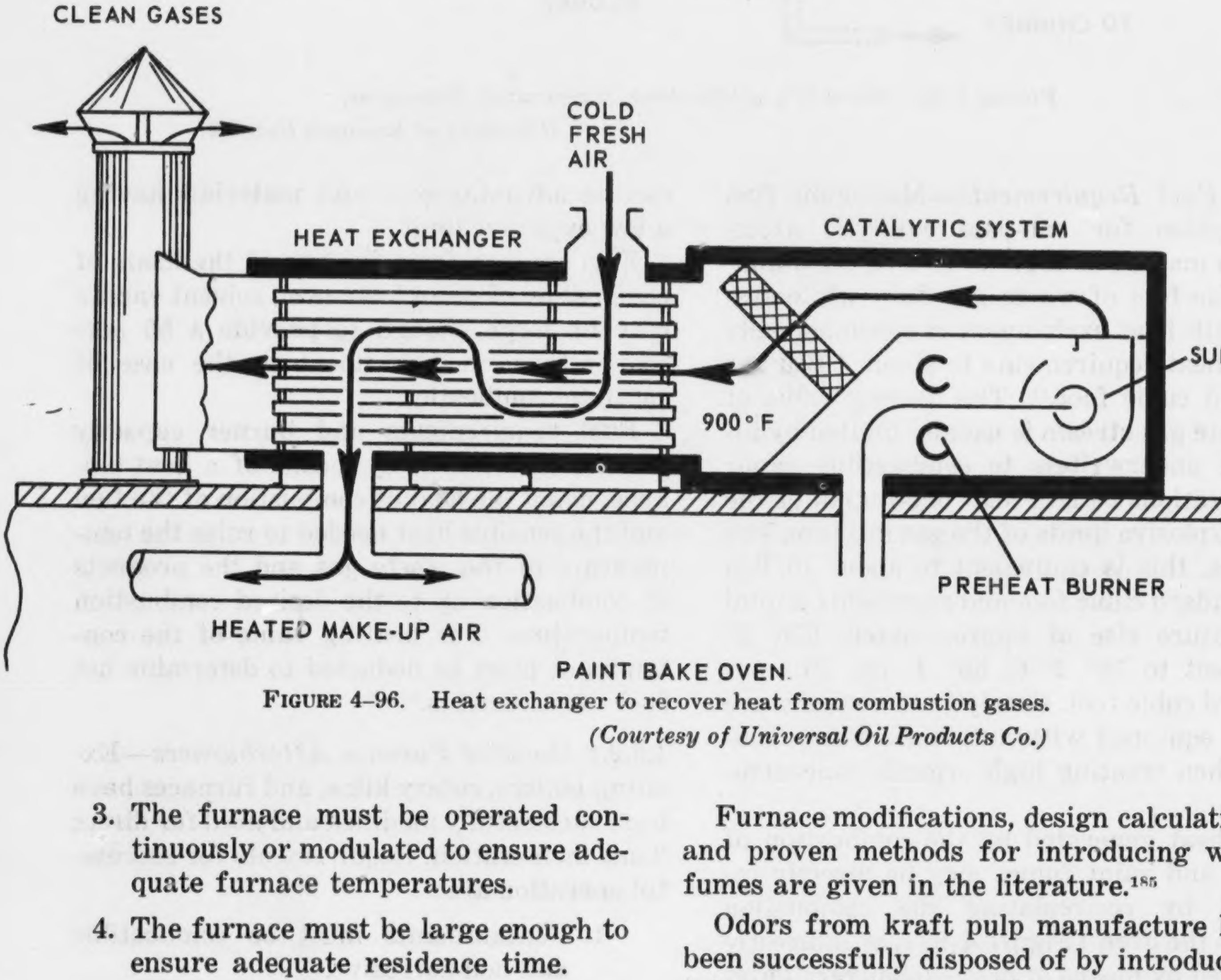
CLEAN GASES
COLD
FRESH
AIR
HEAT EXCHANGER
CATALYTIC SYSTEM
SUPPLY FAN
900° F
PREHEAT BURNER
HEATED MAKE-UP AIR
PAINT BAKE OVEN.

FIGURE 4–96. Heat exchanger to recover heat from combustion gases.
(Courtesy of Universal Oil Products Co.)

3. The furnace must be operated continuously or modulated to ensure adequate furnace temperatures.
4. The furnace must be large enough to ensure adequate residence time.
5. Conditions must be such that there is little or no deposition of particulate matter on the burner or furnace walls.

Furnace modifications, design calculations, and proven methods for introducing waste fumes are given in the literature.[185]

Odors from kraft pulp manufacture have been successfully disposed of by introduction into a modified furnace kiln with fuel savings of over $450 per month.[209, 210]

4.8.2.8 Hood and Duct Design Considerations—Furnace inlet gases, and vapors from

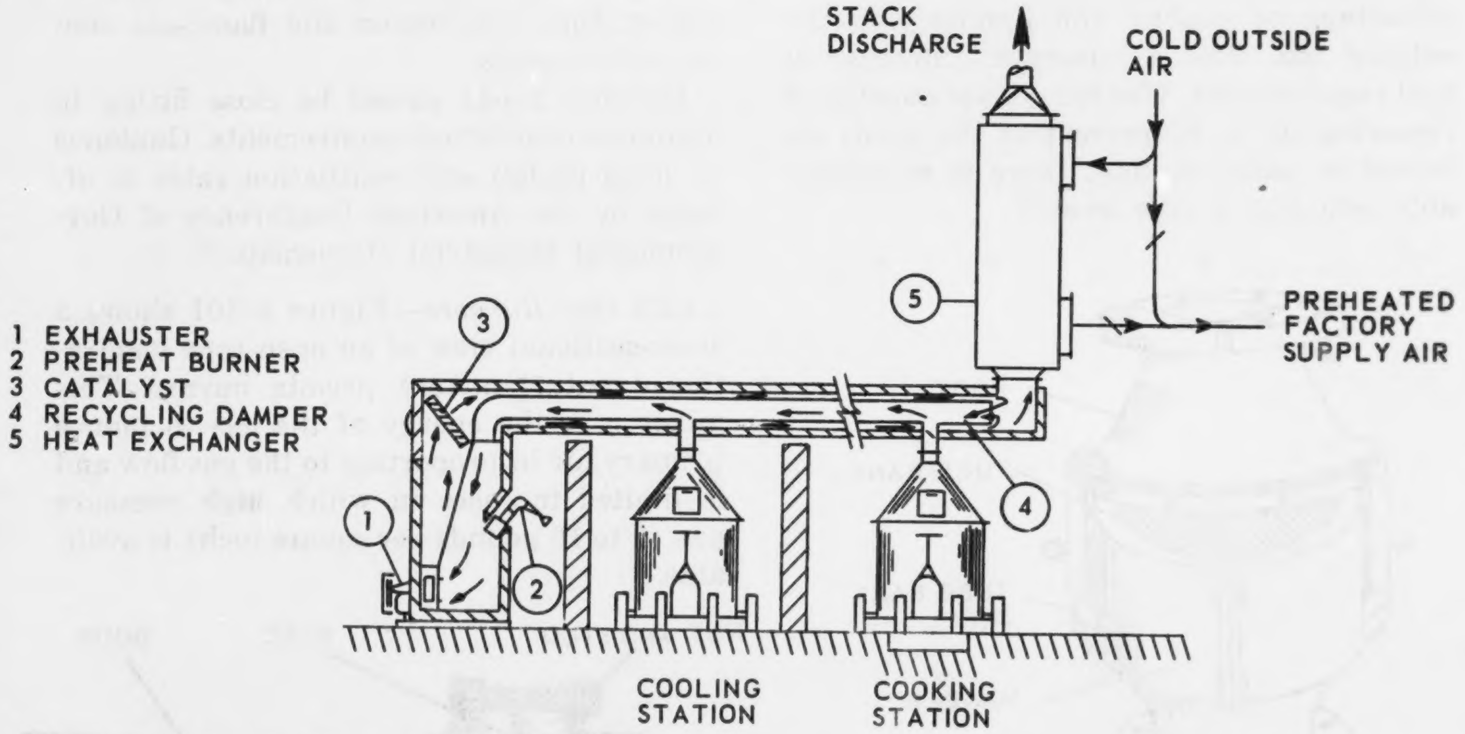
STACK DISCHARGE
COLD OUTSIDE AIR
PREHEATED FACTORY SUPPLY AIR
1 EXHAUSTER
2 PREHEAT BURNER
3 CATALYST
4 RECYCLING DAMPER
5 HEAT EXCHANGER
1
2
3
4
5
COOLING STATION
COOKING STATION

FIGURE 4–97. Integration of fume disposal from a kettle cooking operation with factory make-up air heating.

(Courtesy of Catalytic Combustion Co.)

paint and varnish cooking kettles, as well as from other sources, must be maintained at temperatures above condensation to avoid exhaust duct fouling. Collection ductwork is usually insulated and may be heated by means of an external duct which serves to recover heat from the flue gas, effecting a reduction in combustor fuel requirements (Figure 4–97).[208]

Duct gas velocities are usually high, ranging from 4000 to 5000 feet per minute, to prevent the settling of particulate matter, to effect a high heat recovery rate between the flue gas and furnace feed gas, and to minimize the danger of flashback and fire hazards.[211,212]

Other safety devices to minimize fire hazards may include diluting vapors to below the lower explosive limits, using flame arrestors, and including a wet scrubber between the direct flame combustor and the vapor source. Dilution of the vapors may be accomplished by recirculation of a portion of the flue gas, with a substantial reduction in fuel requirements, as shown in Figure 4–97.[208–213]

Flame arrestors may consist of a packed bed of pebbles, metal tower packing, aluminum rings (Figure 4–98), or corrugated metal gridwork (Figure 4–99), in conjunction with a blast gate or other pressure release device. Flashback through the bed is prevented by bed gas velocities in excess of flame propagation velocities, by pressure drop, as well as by cooling the flame to below combustion temperatures.[213, 214]

Other types of flame arrestors include spray chambers, wet seals, and dip legs (Fig-

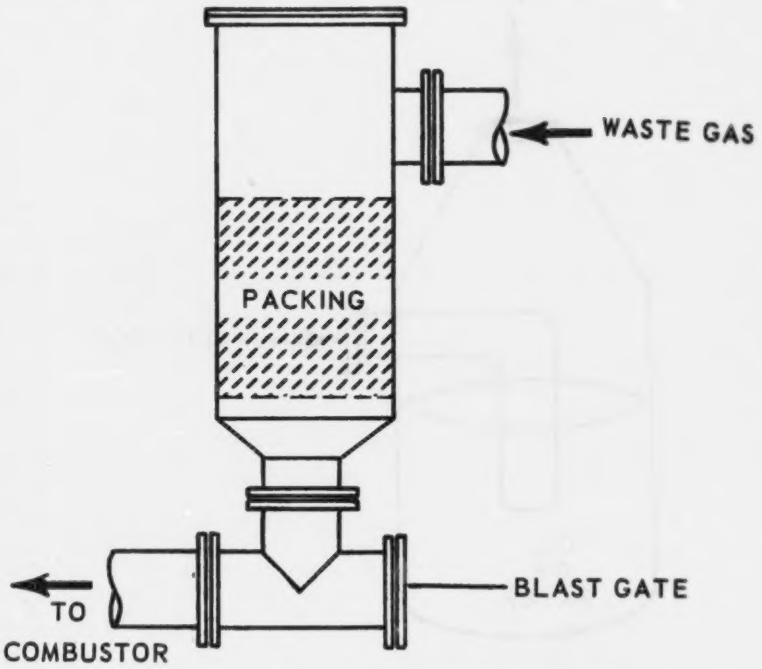
WASTE GAS
PACKING
BLAST GATE
TO COMBUSTOR

FIGURE 4–98. Packed bed flame arrester.

ure 4–100). Wet flame arrestors have the disadvantage of cooling and humidifying the exhaust gas, with a consequent increase in fuel requirements. Wet sprays are capable of removing up to 80 percent of the solids involved in paint making; there is no noticeable reduction in odor level.[185]

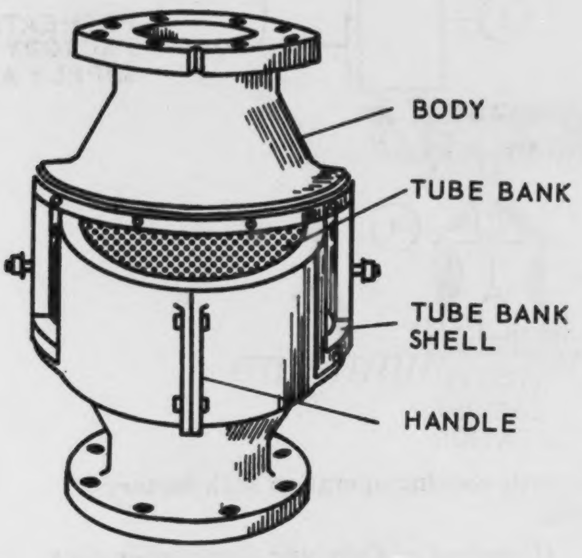

FIGURE 4–99. Corrugated metal flame arrester with cone removed and tube bank pulled partly out of body.

(Courtesy of General Precision Systems, Inc.)

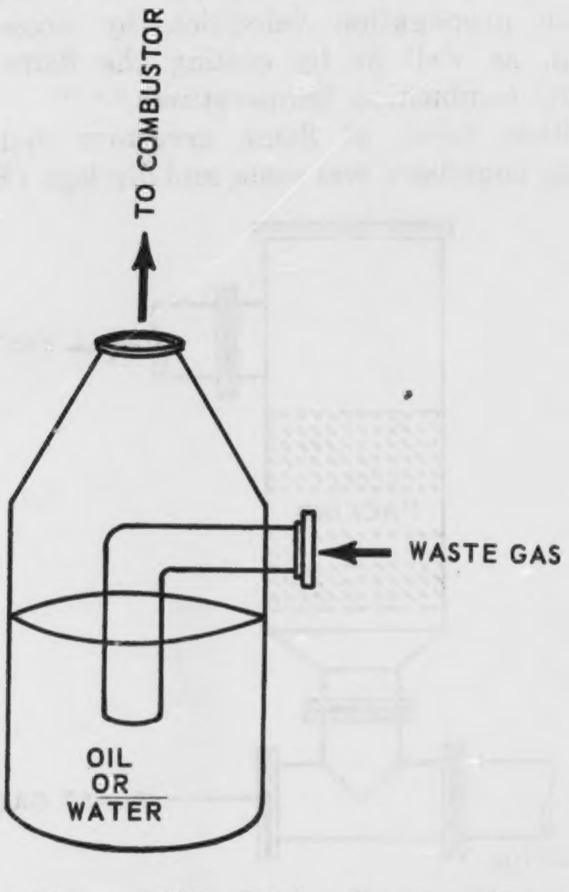

FIGURE 4–100. Dip leg flame arrester.

Other safety devices include high- and low-temperature combustion and flame-out control instruments.

Exhaust hoods should be close fitting to minimize ventilation requirements. Guidance on hood design and ventilation rates is offered by the American Conference of Governmental Industrial Hygienists.[215]

4.8.2.9 Gas Burners—Figure 4–101 shows a cross-sectional view of an open-type inspiration (venturi mixer) premix burner. This mixer uses the energy of the gas to induce primary air in proportion to the gas flow and is limited to cases in which high pressure gas (5 to 10 pounds per square inch) is available.

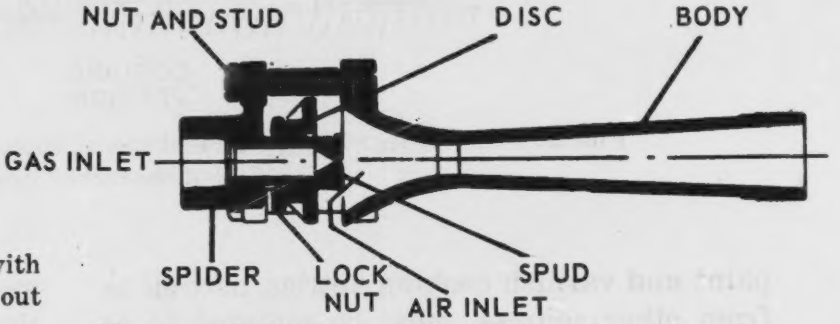

FIGURE 4–101. Cross-sectional view of open-type inspirational premix burner.

Luminous flames may be produced by conventional burners by operation at low capacity and by restricting air supply. Minimum burner capacity is determined by the burner throat velocity at which flashback can occur.[212, 216, 217] The turndown ratio (ratio of maximum to minimum flow rate for satisfactory burner operation) will range from 3:1 to 5:1.

Pressure-type burners, illustrated in Figure 4–102, permit a higher rate of heat release within a relatively small space and are available in a multitude of designs for special applications. They are characterized by a single mixing port or nozzle which produces a short hot flame. Gas premixing is accomplished by use of forced inlet combustion air, usually supplied by a fan. This type of burner has a high turndown ratio and is capable of producing an accurate control of the gas combustion mixture.

Waste gas may be used as a source of primary and secondary air, with a consequent reduction in fuel requirements, if the oxygen

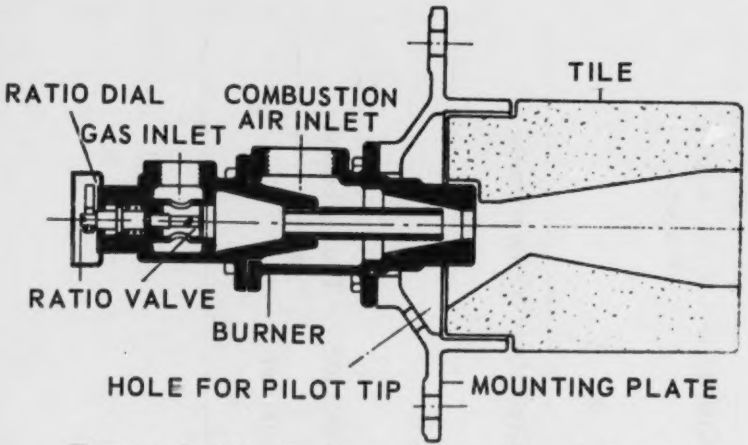

FIGURE 4–102. Cross-sectional view of forced air, premix, multiple-port burner.

content is high and the gas is free from deposit-forming solids.

Burners of the cyclone design, shown in Figure 4–88, are usually mounted to fire tangentially into the combustion chamber and to assist in the cyclonic motion and mixing of the furnace atmosphere. Burners must be capable of continuous modulation to accommodate changes in waste gas flow rates.[185, 202, 215, 218]

To prevent the emission of smoke when the flame is operated to produce a luminous flame, secondary air or waste gas may be introduced above the burner.

Combustion intensity may be further increased by the use of forced air, premixing, multiple-port burners of the type shown in Figure 4–103. Combustion intensities as high as 500 Btu per cubic foot per second have been obtained using a combination of multiple port burners and flame impingement on the surface of refractory brick which acts as a catalytic surface.[182] Typical uses and combustion characteristics for a number of burners are listed in Table 4–14.

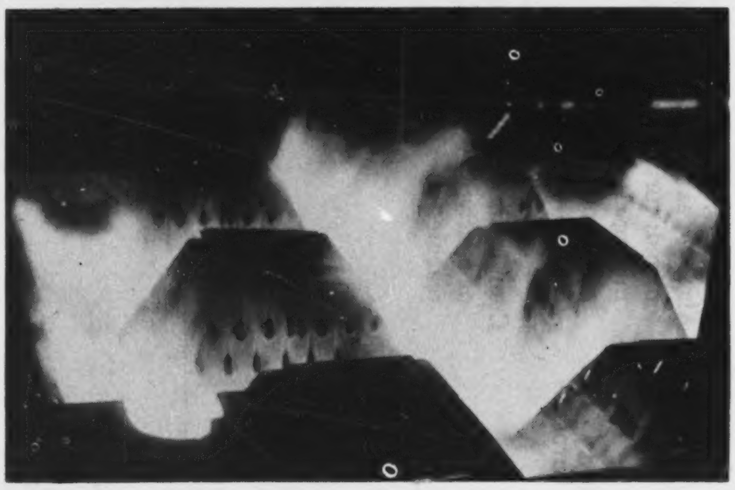

FIGURE 4–103. Multiple-port high-intensity premix burner.

(Courtesy of Maxon Premix Burner Company)

The combustion intensity of a given burner is related to the furnace temperature and fuel composition as indicated in the equation:[198]

$$CI = k \cdot p^2 \cdot T_a \cdot {}^{-3/2}\, C_f \cdot C_o \cdot e^{-A/RT_a} \qquad (10)$$

Where: CI = combustion intensity (Btu/ft^3 sec atm);
k is a constant;
p = atmospheric pressure;
T_a = furnace atmosphere temperature °absolute;
C_f, C_o = fuel and oxygen concentration;
e = natural log base;
A = energy of activation (approximately 42,000 calories/gm atom); and
R = universal gas law constant.

A heat loss of approximately 5 percent from the combustion gas can reduce combustion gas temperature and reduce combustion intensity by as much as 20 percent, with a consequent reduction in afterburner combustion efficiency. Hence it is important that combustion zone heat losses be kept at a minimum. Heat losses can be reduced by proper insulation and by shielding the burner from cold objects, such as ironwork, heat exchangers, masonry or even the sky.

Combustion efficiency is improved if combustion takes place at the base of the furnace and the waste gases pass upward. This minimizes opportunity for channeling and bypassing.

4.8.2.10 Construction Materials—Afterburner surfaces exposed to high temperatures and erosive or corrosive conditions must be constructed of alloys capable of withstanding high temperatures or must be lined with refractory materials.

Metals—Temperatures at which alloy steels are used are limited by Underwriters' Laboratories, Inc. to approximately 200° F below the temperature at which scale formation occurs. Martensitic and ferritic stainless steels are recommended for use in areas that are exposed to wide ranges of temperature

Table 4-14.—GAS BURNER CLASSIFICATIONS

Classification	Extent of mixture of air and gas	Velocity of mixture through nozzle, ft/min	Mixing method	Required gas pressure	Required air pressure	Temperature range, °F	Combustion speed	Combustion intensity, approximate maximum heat release per cubic foot of combustion chamber space	Typical burner assemblies
Atmospheric or low-pressure burner system.	Partial, usually less than 50% of air required for combustion.	50 to 1,200	Gas jet mixer or injector using low-pressure gas.	Under 1 lb.	0	100° to 1200°	Very slow	10 Btu/ft^3/sec	Ring burners Pipe burners Torch burners Box burners Immersion burners Wheel burners
Blast or high-pressure burner system.	Air and gas not mixed; low-velocity stratified or diffused in combustion chamber.	400 to 10,000	Not mixed until in combustion zone.	Under 4 oz.	Under 4 oz.	600° to 2400°	Slow	28 Btu/ft^3/sec	Diffusion burners Radiant flame burners Variflame burners Radiant tube burners Static pressure burners
	Air and gas not mixed; turbulent mixing close to nozzle but in combustion chamber.	400 to 36,000	Not mixed until in combustion zone.	4 to 16 oz.	4 to 32 oz.	1000° to 2800°	Fast	70 Btu/ft^3/sec	Nozzle mixing burner.
	Completely mixed or nearly so before reaching nozzle.	1,200 to 36,000	Premixed by air jet mixer.	4 oz.	4 to 32 oz.	1200° to 3000°	Very fast	70 Btu/ft^3/sec	Open burners
			Gas jet mixer HP gas.	1 to 25 lb.	0				
			Mechanical mixer	4 oz.	0			555 to 1400 Btu/ft^3/sec	Tunnel burners
			Combination of the above.						

and to corrosive conditions.[218] Temperature limitations for other metals and alloys are determined by design stress and safety requirements.[207]

Refractories—Refractories used in direct flame afterburners increase radiant heat transfer, insulate, act as a support structure, and resist abrasion and corrosion. In so doing, they must be capable of withstanding thermal shock. Fire clay refractories are commonly used in incinerator and afterburner construction because of low cost, spall resistance, and long service life. Fire clay refractory bricks are classified (Table 4–15) into maximum service classes according to American Society for Testing and Materials standards (ASTM).[202] Their softening points, as determined by pyrometric cone equivalent (PCE) help determine their maximum service class.[219] Other requirements include limits on shrinkage, spalling loss, and deformation under load. Castable fire clay refractories commonly used (Table 4–16) are of two ASTM classes.[217]

Table 4–15.—ASTM CLASSIFICATION OF FIRE CLAY REFRACTORIES

Refractory type	PCE	Temperature, °F
Low heat duty	19	2768
Intermediate heat duty	29	2984
High heat duty	21–32	3056–3092
Super duty	33	3173

Table 4–16.—COMMONLY USED CASTABLE FIRE CLAY REFRACTORIES

ASTM No.	Temperature, °F	Density, lb/ft^3	Special properties
24	2400	70–85	Insulating light weight
27	2700	110–125	General purpose

Service temperature range and physical properties of various refractories for corrosive conditions are shown in Figures 4–104 and 4–105 and in Table 4–17. The literature contains further information.[202, 203, 219]

4.8.2.11 Typical Applications—A summary of the afterburner applications is presented in Table 4–18. The information was taken from published literature and manufacturers' bulletins.

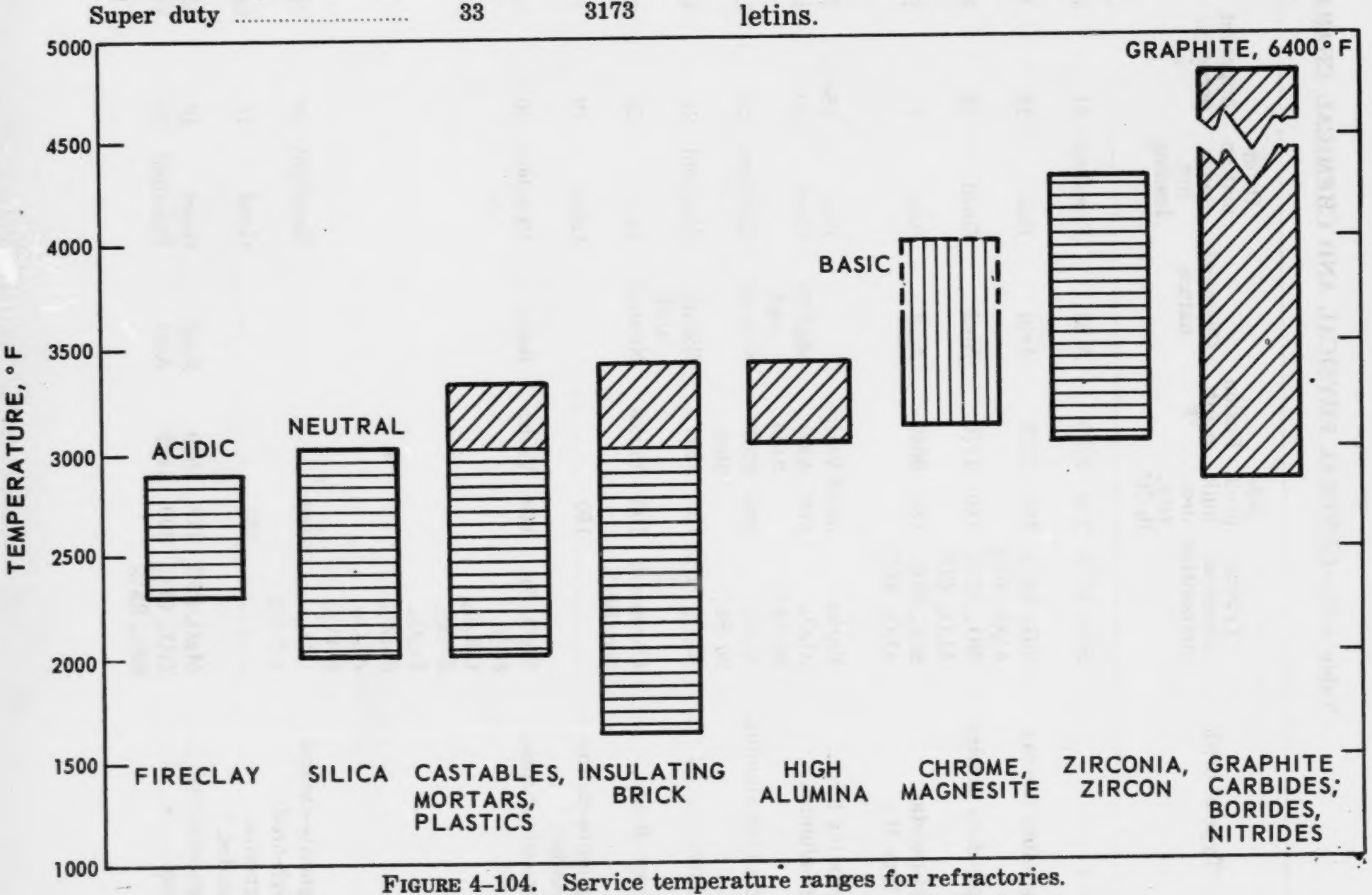

FIGURE 4–104. Service temperature ranges for refractories. (*Courtesy of McGraw-Hill Book Co.*)

Table 4-17.—GENERAL PHYSICAL AND CHEMICAL CHARACTERISTICS OF CLASSES OF REFRACTORY BRICK

Type of brick	Typical chemical composition	Approx. bulk density, lb/ft^3	Fusion point, °F	Chemical nature	Deformation under hot loading	Apparent porosity, %	Permeability	Hot strength	Thermal shock resistance	Chemical resistance	
										to acid	to alkali
Silica	SiO_2, 95%	115	3100	Acid	Excellent	21	High	Excellent	Poor [a]	Good	Good at low temperatures.
High-duty fireclay	SiO_2, 54% Al_2O_3, 40%	134	3125	Acid	Fair	18	Moderate	Fair	Fair	Good	Good at low temperatures.
Super-duty fireclay	SiO_2, 52% Al_2O_3, 42%	140	3170	Aicd	Good	15	High	Fair	Good	Good	Good at low temperatures.
Acid-resistant (type H).	SiO_2, 59% Al_2O_3, 34%	142	3040	Acid	Poor	7	Low	Poor	Good	Insoluble in acids except HF and boiling phosphoric.	Very resistant in moderate concentrations.
Insulating brick	Varies	30-75	Varies	--------	Poor	65–85	High	Poor	Excellent	Poor	Poor
High-alumina	Al_2O_3, 50–85%	170	3200–3400	Slightly acid.	Good	20	Low	Good	Good	--------	--------
Extra-high alumina	Al_2O_3, 90–99%	185	3000–3650	Neutral	Excellent	23	Low	Excellent	Good	Good except for HF and aqua regia.	Very slight attack with hot solutions.
Mullite	Al_2O_3, 71%	153	3290	Slightly acid.	Excellent	20	Low	Good	Good	Insoluble in most acids.	Slight reaction
Chrome-fired	Chrome ore, 100%	195	Varies	Neutral	Fair	20	Low	Good	Poor	Fair to good	Poor
Magnesite-chrome bonded. [b]	--------	190	--------	--------	Good	12	Very low.	Good	Excellent	--------	--------
Magnesite-chrome fired.	MgO, 50–80% CR_2O_3, 5–18% Fe_2O_3, 3–13% Al_2O_3, 6–11% SiO_2, 1.2–5%	180	Varies	Basic	Excellent	20	High	Good	Excellent	Fair except to strong acids.	Fair resistance at low temperatures.
Magnesite-chrome high-fired.		180	--------	--------	Excellent	18	High	Excellent	Excellent	--------	--------
Magnesite-bonded. [b]	--------	181	--------	--------	Good	11	Low	Good	Good	Soluble in most acids.	Good resistance at low temperatures.
Magnesite-fired	MgO, 95%	178	3900	Basic	Good	19	Moderate	Good	Good	--------	--------
Zircon	ZrO_2, 67% SiO_2, 33%	200	3100[c]	Acid	Excellent	25	Very low	Excellent	Good	Very slight	Very slight

Zirconia (stabilized).	ZrO_2, 94% CaO, 4%	245	4800	Slightly acid.	Excellent	23	Low	Excellent	Excellent	Very slight	Very slight
Silicon-carbide	SiC, 80–90%	160	4175	Slightly acid.	Excellent	15	Very low	Excellent	Excellent	Slight reaction with HF.	Attacked at high temperatures.
Graphite	C, 97%	105	6400	Neutral	Excellent	16	Low	Excellent	Excellent	Insoluble	Insoluble

[a] Good above 1200° F.
[b] Chemically bonded.
[c] Dissociates above 3100° F.

Table 4–18.—SUMMARY OF AFTERBURNER APPLICATIONS AND LITERATURE REFERENCES

Applications	References	
	Catalytic	Flame
Acrylate polymerization	204	178
Asphalt blowing and saturating [a]	204	----------
Automotive paint baking	*227* [b], 204, 195	----------
Bakelite manufacturing	----------	*225*
Bonding and burnoff	204, *225*	----------
Burnoff ovens [a]	204	178
Carbon furnaces [a]	204, 223	178
Chemical processing	194	*192*, 201
Coffee roasting [a]	204, *224*	*209*, *224*
Coil and strip coating	204	179
Corn popping [a]	204	----------
Cupola gas [a]	----------	209
Deep fat frying [a]	204	----------
Fabric curing	185	185
Fish and vegetable oil processing [a]	204	----------
Food processing	204	----------
Foundry core baking [a]	185, 204	----------
Fungicide manufacture [a]	204	----------
Grinding wheel sintering	*194*	----------
Hardboard coating and curing	204	----------
Incinerators [a]	----------	*228*
Kraft paper manufacture	----------	*209*, *222*
Metal decorating [a]	185, 204	178
Metal chip drying	204	----------
Nut roasting	204	----------
Oil hydrogenation [a]	204	----------
Oil quenching [a]	204	----------
Oil sulfurization	204	178, 195, 220
Paint and varnish cooking [a]	204, 227	209, 220, 225, 226
Paper coating	204	----------
Pharmaceutical manufacture	204	----------
Phthalic and maleic anhydride manufacture [a]	*185*, *204*, *227*	*178*, *220*
Potato chip cooking [a]	204	178
Printing [a]	*204*, 221	178
Rendering [a]	204	178, 185
Resin manufacturing and acrylate polymerization [a]	204	*178*, *220*
Rice browning [a]	*204*	----------
Sewage treatment	204	203, 229
Smoke abatement [a]	----------	228, 230
Smoke houses [a]	----------	185, 209
Stationary diesel engines	194, 227	----------
Synthetic rubber manufacture	204	200
Tar coating	204	----------
Textile finishing	----------	198
Vitamin manufacture	204	----------
Wax burnout, investment casting [a]	185, 204	----------
Wire enameling [a]	*194*, 204, 227	178, *226*

[a] Involves discharge of particulate matter.
[b] Italicized references contain quantitative data.

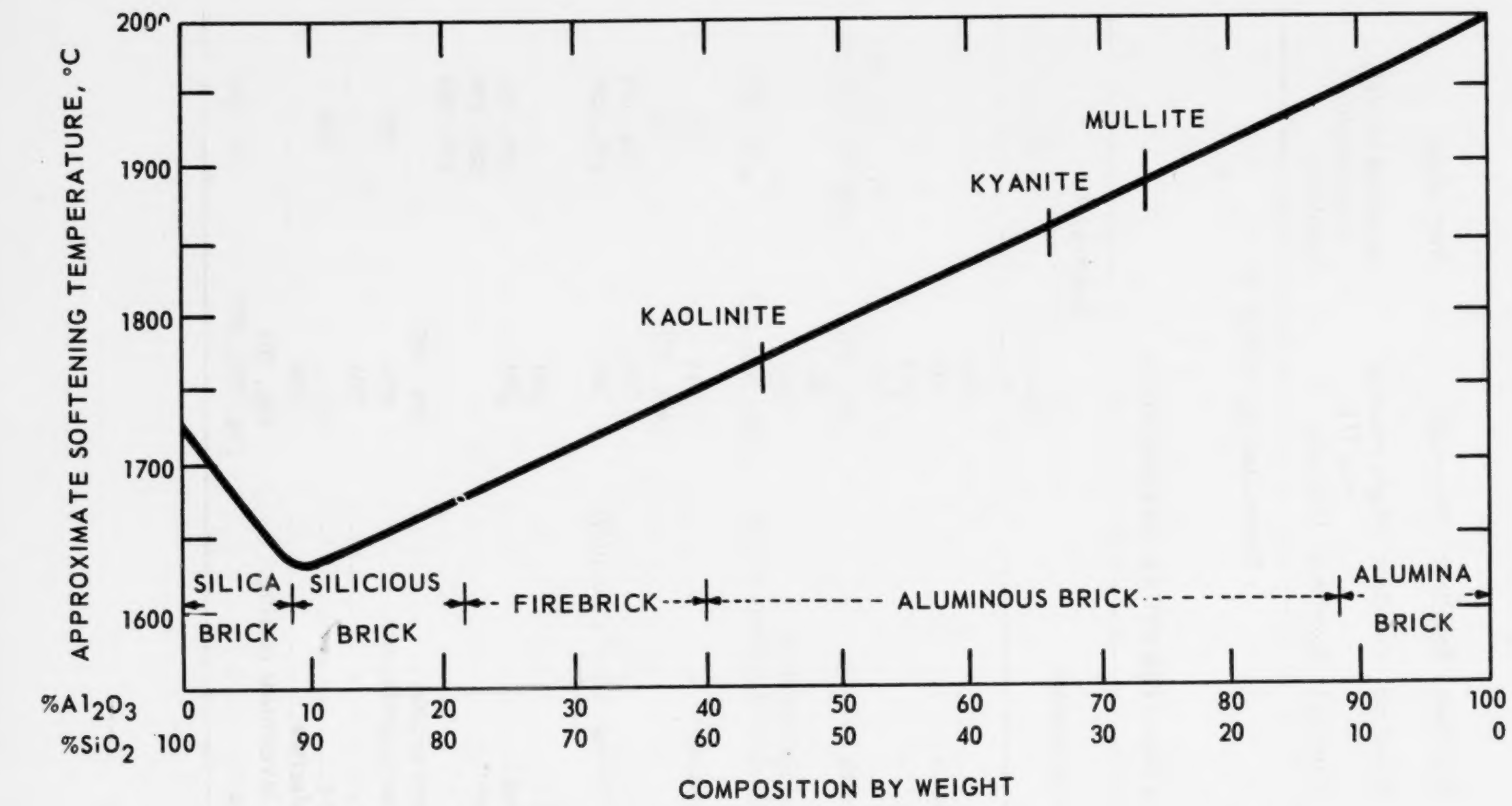

FIGURE 4–105. Degree of refraction for alumina-silica system products.

(Courtesy of Chemical Engineering Magazine)

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5. EMISSION FACTORS FOR PARTICULATE AIR POLLUTANTS

An emission factor is a statistical average of the rate at which pollutants are emitted from the burning or processing of a given quantity of material. Emission factors can also be established on the basis of some other meaningful parameter, such as the number of miles traveled in a vehicle. To determine emission factors, available reliable data on emissions from a particular source or group of sources are gathered and correlated with information on process use. The individual emission factors derived are tabulated, and either an average or a range of values is selected for use.

Some emission factors are based on very limited data; others are based on extensive data that are highly variable; and still others are based on extensive, consistent data. It is, therefore, important that the accuracy of the data on which an emission factor is based be evaluated before the factor is used for estimating emissions.

In general, the emission factors for particulate air pollutants are not precise indicators of what particulate emissions might be from any single process even though all the details of the process are known. Emission factors are more valid when applied to a number of processes.

Emission factors listed in Table 5-1 are taken from *Compilation of Air Pollutant Emission Factors*, Public Health Service publication No. 999-AP-42, except where noted. The factors are for uncontrolled sources except as qualified in the table. Examples of how emission factors are used follow.

Table 5-1.—PARTICULATE EMISSION FACTORS[1]

Source	Particulate emission rate[a]
Fuel combustion—stationary sources:	
Coal:	
Pulverized:	
General (anthracite and bituminous)	16A[b] lb/ton of coal burned
Dry bottom (anthracite and bituminous)	17A lb/ton of coal burned
Wet bottom (anthracite and bituminous):	
Without fly ash reinjection	13A lb/ton of coal burned
With fly ash reinjection	24A[c] lb/ton of coal burned
Cyclone (anthracite and bituminous)	2A[d] lb/ton of coal burned
Spreader stoker (anthracite and bituminous):	
Without fly ash reinjection	13A lb/ton of coal burned
With fly ash reinjection	20A[c] lb/ton of coal burned
All other stokers (anthracite and bituminous):	
Greater than 10×10^6 Btu/hr	5A lb/ton of coal burned
Less than 10×10^6 Btu/hr	2A[d] lb/ton of coal burned
Hand-fired equipment (bituminous coal only)	20 lb/ton of coal burned
Residual oil:	
Greater than 100×10^6 Btu/hr	10 lb/1000 gallons of oil burned
Less than 100×10^6 Btu/hr	23 lb/1000 gallons of oil burned
Distillate oil:	
10 to 100×10^6 Btu/hr	15 lb/1000 gallons of oil burned
Less than 10×10^6 Btu/hr	8 lb/1000 gallons of oil burned

Table 5–1 (Continued).—PARTICULATE EMISSION FACTORS[1]

Source	Particulate emission rate[a]
Fuel combustion—stationary sources (continued):	
Natural gas:	
Greater than 100×10^6 Btu/hr	15 lb/million ft^3 of gas burned
10 to 100×10^6 Btu/hr	18 lb/million ft^3 of gas burned
Less than 10×10^6 Btu/hr	19 lb/million ft^3 of gas burned
Wood[2]	10 lb/ton of wood burned
Fuel combustion—mobile sources:	
Gasoline-powered motor vehicle	12 lb/1000 gallons consumed
Diesel-powered vehicle	110 lb/1000 gallons consumed
Aircraft:	
Jet (fan-type):	
4 engine	7.4 lb/flight[e]
3 engine	5.6 lb/flight
2 engine	3.8 lb/flight
1 engine	1.9 lb/flight
Jet (conventional):	
4 engine	34.0 lb/flight[e]
3 engine	25.5 lb/flight
2 engine	17.0 lb/flight
1 engine	8.5 lb/flight
Turboprop:	
4 engine	2.5 lb/flight[e]
2 engine	0.6 lb/flight
Piston:	
4 engine	1.4 lb/flight[e]
2 engine	0.6 lb/flight
1 engine	0.3 lb/flight
Solid waste disposal:	
Open burning of leaves and brush	17 lb/ton of refuse burned
Open-burning dump	16 lb/ton of refuse burned
Municipal incinerator	17 lb/ton of refuse burned
On-site commercial and industrial multiple-chamber incinerator (Los Angeles design)	3 lb/ton of refuse burned
Single-chamber incinerator	10 lb/ton of refuse burned
Domestic gas-fired incinerator	15 lb/ton of refuse burned
On-site residential flue-fed incinerator	28 lb/ton of refuse burned
Process industries—(specific examples):	
Chemical industry:	
Paint and varnish manufacture:	
Varnish cooker	60–120 lb/ton of feed
Alkylresin production—total operation	80–120 lb/ton of feed
Cooking and blowing of oils	20–60 lb/ton of feed
Heat polymerization acrylic resins	20 lb/ton of feed
Phosphoric acid manufacture—thermal process absorber tail gas with control (acid mist).	0.2–10.8[f] lb/ton of phosphorus burned
Sulfuric acid manufacture—contact process (acid mist)	0.3–7.5 lb/ton of acid produced
Food and agriculture industries:	
Coffee roasting:	
Direct fired roaster	7.6 lb/ton of green beans
Indirect fired roaster	4.2 lb/ton of green beans
Stoner and cooler	1.4 lb/ton of green beans
Instant coffee spray dryer—always controlled with cyclone and wet scrubber.	1.4 lb/ton of green beans
Cotton ginning operation (includes cotton gin and incineration of cotton trash).	11.7 lb/bale of cotton (500 lb)
Feed and grain mills:	
General with 90 percent efficient cyclones	6 lb/ton of product
Wheat air cleaner with cyclone	0.2 lb/ton of product

Table 5–1 (Continued).—PARTICULATE EMISSION FACTORS[1]

Source	Particulate emission rate[a]
Feed and grain mills (continued):	
Barley flour mill with cyclone	3.1 lb/ton of product
Alfalfa meal mill with settling chamber and cyclone	4.0 lb/ton of product
Orange pulp dryer with cyclone	11.3 lb/ton of product
Starch manufacture—natural gas direct-fired flash drier	8 lb/ton of starch
Primary metal industry:	
Iron and steel manufacture:	
Sintering machine gases	20 lb/ton of sinter
Sinter machine discharge	22 lb/ton of sinter
Open hearth furnace:	
Oxygen lance[g]	22 lb/ton of steel
No oxygen lance[g]	14 lb/ton of steel
Basic oxygen furnace[g]	46 lb/ton of steel
Electric arc furnace:	
Oxygen lance[g]	11 lb/ton of steel
No oxygen lance[g]	7 lb/ton of steel
Blast furnace:	
Ore charging[g]	110 lb/ton of iron
Agglomerate charging[g]	40 lb/ton of iron
Scarfing	3 lb/ton of steel processed
Coking operations—charging. pushing. quenching	2 lb/ton of coal
Secondary metal industry:	
Aluminum smelting:	
Chlorination—lancing of chlorine gas into molten metal bath	1000 lb/ton of chlorine used
Crucible furnace	1.9 lb/ton of metal processed
Reverberatory furnace	4.3 lb/ton of metal processed
Sweating furnace	32.2 lb/ton of metal charged
Brass and bronze smelting:	
Crucible furnace	3.9 lb/ton of metal charged
Electric furnace	3.0 lb/ton of metal charged
Reverberatory furnace	26.3 lb/ton of metal charged
Rotary furnace	20.9 lb/ton of metal charged
Gray iron foundry:	
Cupola	17.4 lb/ton of metal charged
Electric induction furnace	2.0 lb/ton of metal charged
Reverberatory furnace	2.0 lb/ton of metal charged
Lead smelting:	
Cupola	300 lb/ton of metal charged
Pot furnace	0.1 lb/ton of metal charged
Reverberatory and sweating furnace	154 lb/ton of metal charged
Magnesium smelting: Pot furnace	4.4 lb/ton of metal charged
Steel foundry:	
Electric arc furnace	15.0 lb/ton to metal charged
Electric induction furnace	0.1 lb/ton of metal charged
Open hearth furnace	10.6 lb/ton of metal charged
Zinc smelting:	
Galvanizing kettles	5.3 lb/ton of metal charged
Calcine kilns	88.8 lb/ton of metal charged
Pot furnaces	0.1 lb/ton of metal charged
Sweating furnace	10.8 lb/ton of metal charged
Mineral product industry:	
Asphalt saturators	3.9[h] lb/ton of asphalt
Asphalt batch plant—rotary drier	5.0 lb/ton of mix
Calcium carbide plant:	
Coke dryer	0.2 lb/ton of product
Electric furnace hood	1.7 lb/ton of product
Furnace room vents	2.6 lb/ton of product

Table 5–1 (Continued).—PARTICULATE EMISSION FACTORS[1]

Source	Particulate emission rate[a]
Secondary metal industry (continued):	
Calcium carbide plant (continued):	
Main stack (vents to atmosphere) exhaust from furnace hoods always passes through impingement scrubbers	2.0 lb/ton of product
Cement manufacture:	
Dry process—kiln	46 lb/barrel of cement
Wet process—kiln	38 lb/barrel of cement
Ceramic and clay processes:	
Ceramic clay—spray drier with cyclone	15 lb/ton of charge
Bisque with scrubber	2 lb/ton of charge
Catalytic material—dried, kiln and cooler with cyclone and scrubber	6 lb/ton of charge
Concrete batch plant—total operation	0.2 lb/yard of concrete
Frit manufacture—frit smelters	16.5 lb/ton of charge
Glass manufacture—soda-lime process with direct fired continuous melting	2.0 lb/ton of glass
Lime production:	
Rotary kiln	200 lb/ton of lime
Vertical kiln	20 lb/ton of lime
Perlite manufacture—expanding furnace	21 lb/ton of charge
Rock wool manufacture:	
Cupola	21.6 lb/ton of charge
Reverberatory furnace	4.8 lb/ton of charge
Blow chamber	21.6 lb/ton of charge
Curing oven	3.6 lb/ton of charge
Cooler	2.4 lb/ton of charge
Rock, gravel and sand production:	
Crushing	20 lb/ton of product
Conveying, screening, shaking	1.7 lb/ton of product
Storage piles—wind erosion	20 lb/ton of product
Petroleum industry:	
Fluid catalytic crackers	0.1 to 0.2[i] lb/ton of catalyst circulated
Moving bed catalytic crackers:	
TCC-type unit	0.05 to 0.15[j] lb/ton of catalyst circulated
HCC-type unit	0.15 to 0.25[j] lb/ton of catalyst circulated
Kraft pulp industry:	
Smelt tank:	
Uncontrolled	20 lb/ton of dry pulp produced
Water spray	5 lb/ton of dry pulp produced
Mesh demister	1–2 lb/ton of dry pulp produced
Lime kiln	94 lb/ton of dry pulp produced
Recovery furnace with primary stack gas scrubber	150 lb/ton of dry pulp produced

[a] Emission rates are those from uncontrolled sources, unless otherwise noted.

[b] Where letter A is shown, multiply number given by the percent ash in the coal.

[c] Value should not be used as emission factor. Values represent the loading reaching the control equipment always used on this type of furnace.

[d] Revised from 5A.

[e] Flight is defined as a combination of a landing and a takeoff.

[f] Depends on type of control.

[g] Based on data from NAPCA Contract No. PH 22–68–65.

[h] Includes only solid particulate matter. In addition, about 65 lb/hr of oil mist may be evolved from asphalt saturators.

[i] Revised from 0.1.

[j] Revised from 0.04.

Coal Combustion

Given: Source burns 10,000 tons per year in a spreader stoker without fly ash reinjection.

85 percent efficient multiple cyclones. Ash content—10 percent (Note: Expressed as the number 10 in making the computation).

From Table 5-1:

Emision factor = 13A pounds per ton of coal, where A equals ash content.

Therefore:

Particulate emissions = (Process weight) (Emission factor) Collection efficiency factor)

Particulate emissions =

$$\left[10{,}000\ \frac{\text{tons of coal}}{\text{year}}\right]$$

$$\left[(13)\,(10)\ \frac{\text{pounds of particulate}}{\text{tons of coal}}\right]$$

$$[1\text{–}0.85] = 195{,}000\ \frac{\text{pounds of particulate}}{\text{year}}$$

Solid Waste Disposal

Given: Commercial operation burning 2,000 tons per year of refuse in multiple-chamber incinerator.

From Table 5-1:

Emission factor—3 pound per ton of refuse

Therefore:

Particulate emissions =

$$\left[2{,}000\ \frac{\text{tons of refuse}}{\text{year}}\right]$$

$$\left[3\ \frac{\text{pounds of particulate}}{\text{tons of refuse}}\right]$$

$$= 6{,}000\ \frac{\text{pounds of particulate}}{\text{year}}$$

Process Industries

Given: Secondary brass and bronze smelting operation with fabric filter 99 percent efficient

Furnace type—electric.

Metal charged into furnace—20,000 tons per year

From Table 5-1:

Emission factor = 3 pounds per ton of metal charged

Therefore:

Particulate emissions =

$$\left[20{,}000\ \frac{\text{tons of metal charged}}{\text{year}}\right]$$

$$\left[3.0\ \frac{\text{pounds of particulate}}{\text{tons of metal charged}}\right]\ [1\text{–}0.99]$$

$$= 600\ \frac{\text{pounds of particulate}}{\text{year}}$$

REFERENCES FOR SECTION 5

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6. ECONOMIC CONSIDERATIONS IN AIR POLLUTION CONTROL

6.1 SELECTION OF CONTROL SYSTEM

Most air pollution emission control problems can be solved in several ways. In order to select the best method of reducing pollutant emissions, each solution should be thoroughly evaluated prior to implementation. Steps such as substitution of fuels and raw materials and modification or replacement of processes should not be overlooked as possible solutions. Such emission reduction procedures often can improve more than one pollution problem. For example, particulate matter and sulfur oxides emissions both may be reduced by switching from high-sulfur coal to natural gas or low-sulfur oil. Such steps also may have the benefit of reducing or eliminating solid waste disposal and water pollution problems. Often it is cheaper to attack two air problems together than to approach each problem individually. If steps such as process alterations and substitution of fuels are not feasible, it may be necessary to use gas cleaning equipment.

Figure 6-1 shows the factors to be considered in selecting of gas cleaning system. The first consideration is the degree of reduction of emissions which may be required to meet emission standards. The degree of emission reduction or the collection efficiency required is dependent upon the relationship between emissions and emission standards as shown at the top of the figure. This is an important factor in making the choice among control equipment alternatives. Although a control system may include two or more pieces of control equipment, collection efficiency, as used in this chapter, applies to individual pieces of control equipment. The usual ranges of collection efficiency for various equipment alternatives are shown in Table 6-1. The important factors to be considered next are the gas stream and particle characteristics of the process itself, as shown in the center of Figure 6-1. High gas temperatures without cooling, for example, preclude the use of fabric filters; explosive gas streams prohibit the use of electrostatic precipitators; and submicron particles cannot generally be efficiently collected with mechanical collectors. A number of factors that relate to the plant facility should also be considered, some of which are listed in Figure 6-1. Each alternative will have a specific cost associated with it, and the components of this cost should be carefully examined. Those alternatives which meet the requirements of both the process and the plant facility can then be evaluated in terms of cost; on this basis, the gas cleaning system may be selected.

Table 6-1.—AIR POLLUTION CONTROL EQUIPMENT COLLECTION EFFICIENCIES[1,2,3]

Equipment type	Efficiency Range (on a total weight basis) percent
Electrostatic precipitator[a]	80 to 90.5+
Fabric filters[b]	95 to 99.9
Mechanical collector	50 to 95
Wet collector	75 to 99+
Afterburner:	
Catalytic[c]	50 to 80
Direct flame	95 to 99

[a] Most electrostatic precipitators sold today are designed for 98 to 99.5 percent collection efficiency.

[b] Fabric filter collection efficiency is normally above 99.5 percent.

[c] Not normally applied in particulate control; has limited use because most particulates poison or desensitize the catalyst.

6.2 COST-EFFECTIVENESS RELATIONSHIPS

Meaningful quantitative relationships between control costs and pollutant reductions are useful in assessing the impact of control on product prices, profits, investments, and value added to the product.* With such

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* Value added is generally considered to be the economic worth added to a product by a particular process, operation, or function.[4]

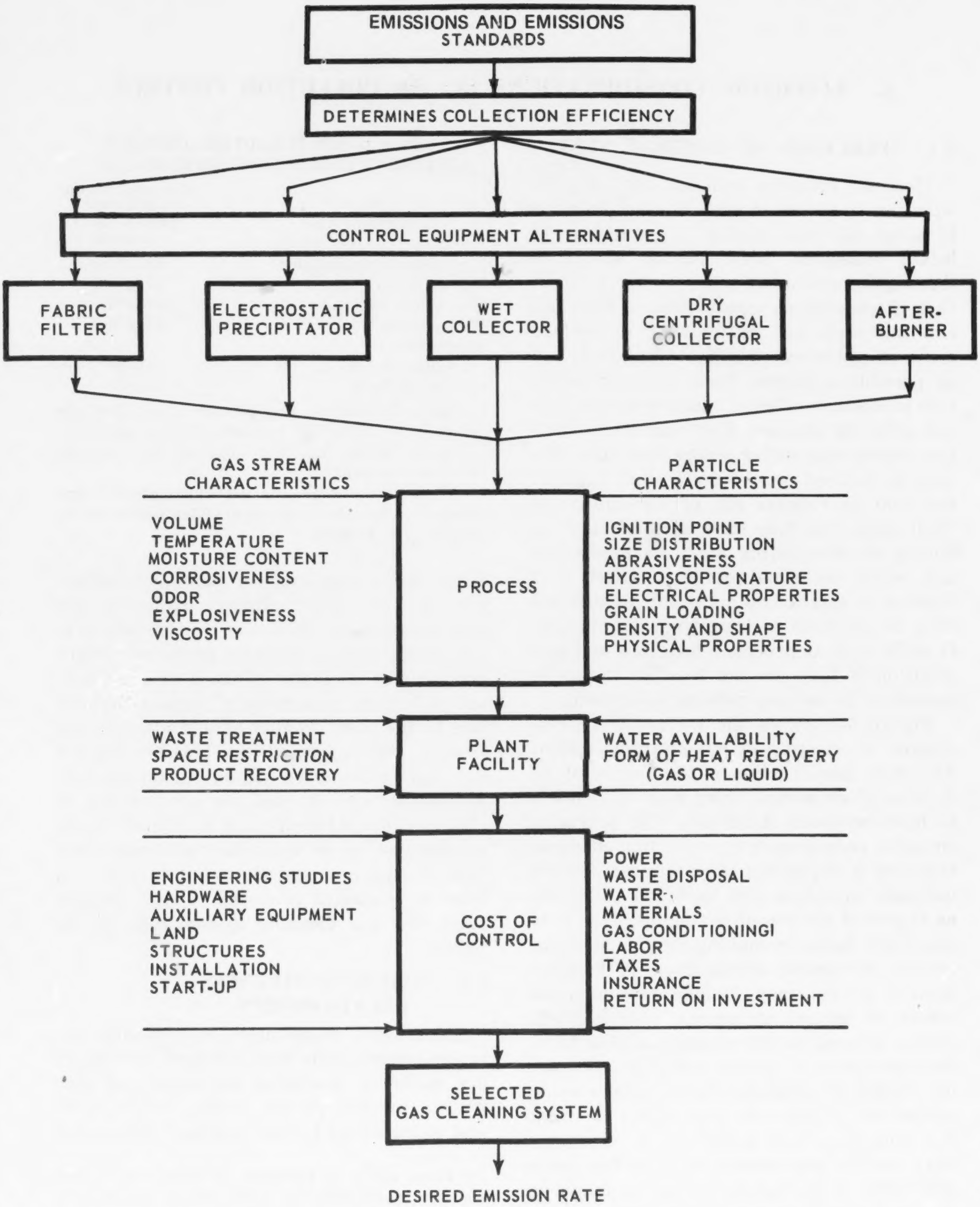
EMISSIONS AND EMISSIONS STANDARDS
DETERMINES COLLECTION EFFICIENCY
CONTROL EQUIPMENT ALTERNATIVES
FABRIC FILTER
ELECTROSTATIC PRECIPITATOR
WET COLLECTOR
DRY CENTRIFUGAL COLLECTOR
AFTER-BURNER
GAS STREAM CHARACTERISTICS
VOLUME
TEMPERATURE
MOISTURE CONTENT
CORROSIVENESS
ODOR
EXPLOSIVENESS
VISCOSITY
PROCESS
PARTICLE CHARACTERISTICS
IGNITION POINT
SIZE DISTRIBUTION
ABRASIVENESS
HYGROSCOPIC NATURE
ELECTRICAL PROPERTIES
GRAIN LOADING
DENSITY AND SHAPE
PHYSICAL PROPERTIES
WASTE TREATMENT
SPACE RESTRICTION
PRODUCT RECOVERY
PLANT FACILITY
WATER AVAILABILITY
FORM OF HEAT RECOVERY (GAS OR LIQUID)
ENGINEERING STUDIES
HARDWARE
AUXILIARY EQUIPMENT
LAND
STRUCTURES
INSTALLATION
START-UP
COST OF CONTROL
POWER
WASTE DISPOSAL
WATER
MATERIALS
GAS CONDITIONING
LABOR
TAXES
INSURANCE
RETURN ON INVESTMENT
SELECTED GAS CLEANING SYSTEM
DESIRED EMISSION RATE

FIGURE 6–1. Criteria for selection of gas cleaning equipment.

relationships at hand the alternates for solution of an air pollution problem can be evaluated for more effective program implementation by the user of the control equipment and by the enforcement agency. These cost-effectiveness relationships sometimes are applied collectively to a meteorological or air quality control region, where they describe the total cost impact on polluters as a result of controlling sources; the discussion here, however, centers around cost-effectiveness as applied to an individual source. Cost-effectiveness is a measure of all costs to the firm associated with a given reduction in pollutant emissions. For computing the costs for a given system, one should consider (1) raw materials and fuels used in the process, (2) alterations in process equipment, (3) control hardware and auxiliary equipment, and (4) disposal of collected emissions.

Figure 6–2 shows an example of a theoretical cost-effectiveness relationship.[5] The actual total costs of control may depart from this curve because some cost elements, such as research and development expenditures and fixed charges (taxes, insurance, depreciation) are not directly related to the operation of the equipment and to the level of emissions in a given year. The cost of control is represented on the vertical axis and the quantity of pollutants emitted on the horizontal axis. Point P indicates the uncontrolled state, in which there are no control costs. As control efficiency improves, the quantity of emissions is reduced and the cost of control increases. In most cases, the marginal cost of control is smaller at the lower levels of efficiency, near point P of the curve. The curve also illustrates that as the cost of control increases, greater increments of cost usually are required for corresponding increments of emission reduction. Process changes sometimes may result in emission reduction without increased costs. Research and development expenditures resulting in new or improved equipment design, improved process operations, or more efficient equipment operations will improve the economics of control. All these factors may substantially reduce control costs at most emission levels and shift the cost of the control curve (CC) as illustrated by CC_1 in Figure 6–3. Note that as control technology develops, the cost of attaining a desired emission level will be reduced from C_a to C_b.

Cost-effectiveness information is useful in emission control decision making. Several feasible systems usually are available for controlling each source of emissions. In most cases, the least-cost solution for each source can be calculated at various levels of control. After evaluating each alternative and after considering future process expansions and more rigid control restrictions, sufficient information should be available on which to base an intelligent control decision.

Cost-effectiveness relationships vary from industry to industry and from plant to plant within an industry. The cost for a given

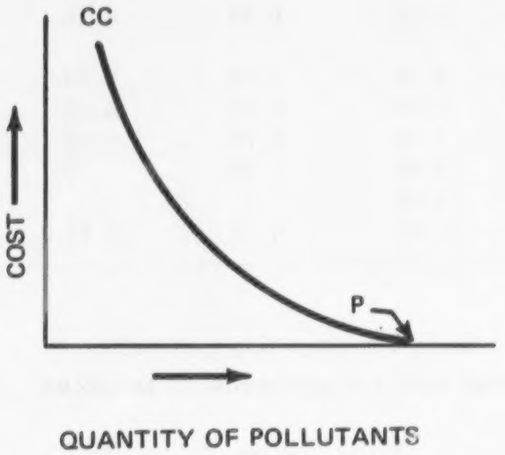

FIGURE 6–2. Cost of control.

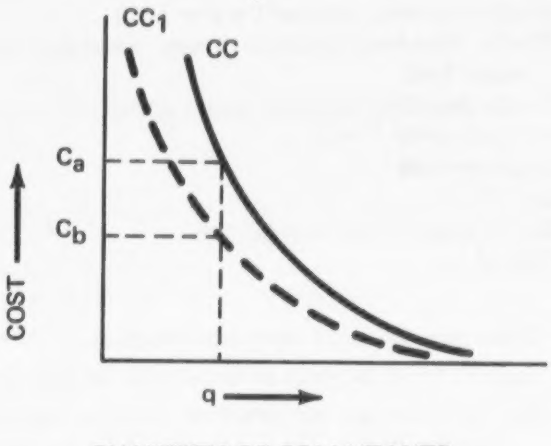

FIGURE 6–3. Expected new cost of control.

control system is significantly dependent on the complexity of the installation and the characteristics of the gas stream and pollutant. Geographical location is another significant factor that influences the total annual cost; for example, the components of annual cost, such as utilities, labor, and the availability of desired sites for waste material, vary from place to place.

6.3 COST DATA

It is the purpose of this chapter to develop basic information and techniques for estimating the costs of installing and operating control equipment. Such information can be useful in developing cost-effectiveness relationships for application of various control systems.

The control cost information included in this chapter is based on experience, a careful study of the literature, and a survey of more than 250 suppliers, users, installers, and operators of air pollution control equipment. The cost information was reviewed by a panel from the gas cleaning equipment industry for reasonableness of data and methodology. The cost data reported reflects 1968 prices, except as noted.

6.4 UNCERTAINTIES IN DEVELOPING COST RELATIONSHIPS

Cost information for control devices is indicated in Section 6.7 where, for various types of equipment, operating capacity is plotted against cost. The upper and lower curves indicate the expected range of costs, with the expected average cost falling approximately in the middle. Although quantitative values for collection efficiency and gas volume capacity are not listed, higher collection efficiency, which involves more intricate engineering design, results in higher costs. Control equipment is designed for a nominal gas volume capacity, but under actual operating conditions the volume may vary. Similarly, the efficiency of control equipment will vary from application to application as particle characteristics, such as wettability, density, shape, and size distribution, differ. For example, a control device designed to operate on 50,000 acfm of gas with a nominal collection of 95 percent may have an effective operating range of from 45,000 to 55,000 acfm, and its collection efficiency may range from 90 to 97 percent.

The effect of these independent variations is to make single point estimates of cost ver-

Table 6-2.—APPROXIMATE COST OF WET COLLECTORS IN 1965 [3]

Type of collector [a]	Cost, dollars/cfm Capacity, cfm			
	1,000	5,000	20,000	40,000
Cyclonic: [b, c]				
Small diameter multiples	0.50	0.30	0.20	0.20
Single chamber, constant water level	1.40	0.45	0.35	0.25
Single chamber, multiple stage, overhead line pressure water feed.	0.95	0.40	0.25	0.20
Single chamber, internal nozzle spray	3.00	1.50	1.00	0.75
Self-induced spray [b, c, d]	0.80	0.40	0.25	0.25
Wet impingement [b, c]	1.00	0.50	0.25	0.25
Venturi [c, d]	3.00	1.50	1.20	0.50
Variable pressure drop inertial [c, d]	1.00	---------	---------	0.30
Mechanical [c, d]	1.75	0.75	0.35	---------

[a] Basic designs, mild steel construction.

[b] Add 30 to 40 percent to base price for fan, drive, and motor (standard construction materials).

[c] Special materials construction costs for 1000 to 40,000 cfm range units are approximately as follows:
Rubber lining—base increase of 65 to 115 percent.
Type 304 stainless steel—base increase of 30 to 60 percent.
Type 316 stainless steel—base increase of 45 to 100 percent.

[d] Add from 10 to 40 percent to base price per additional stage as in some cyclonic and wet impingement designs.

sus size and efficiency difficult to determine. Based on the data available, all estimates must be constructed over an interval of uncertainty for each of the three variables. To make the cost estimation problem manageable in this report, nominal high, medium, and low collection efficiencies have been selected for each type of control equipment, except fabric filters. For fabric filters, the nominal high, medium, and low curves reflect construction variations. The purchase, installed, and total annualized costs of operation are plotted for each of the three efficiency levels over the gas volume range indicated. Purchase, installed, and total annualized costs for fabric filters are plotted for variations in filter construction and cleaning methods.

Generalized categories of control equipment are discussed rather than specific designs because of uncertainties in size, efficiency, and cost. If required, more detailed information on the cost of various engineering innovations (e.g., packed towers of specific design to accommodate a corrosive gas stream) should be requested from the manufacturers of the specific equipment. Cost variations associated with wet collectors are reported in Table 6–2.[3]

Other difficulties exist in developing cost information for existing control devices, especially cost estimates on the maintenance and operation of control equipment. Individual firms may remember what a control device cost originally, but they may forget what it costs to install and operate. In addition, internal bookkeeping and auditing systems often bury these expenditures in total plant operating costs. For example, water and electricity used by a control operation are not always separately metered and accountable as a specific air pollution control cost item. Some of these costs can be identified and assessed on the basis of industrial experience or engineering estimates.

6.5 DESCRIPTION OF CONTROL COST ELEMENTS

6.5.1 General

The actual cost of installing and operating air pollution control equipment is a function of many direct and indirect cost factors. An analysis of the control costs for a specific source should include an evaluation of all relevant factors, as outlined in Figure 6–4. The control system must be designed and operated as an integral part of the process; this will minimize the cost of control for a given emission level. The definable control costs are those that are directly associated with the installation and operation of control systems. These expenditure items from the control equipment user's point of view have a breakdown for accounting purposes as follows:

- Capital Investment:
  - Engineering studies
  - Land
  - Control hardware*
  - Auxiliary equipment*
  - Operating supply inventory
  - Installation*
  - Startup
  - Structure modification
- Maintenance and Operation:
  - Utilities*
  - Labor*
  - Supplies and materials*
  - Treatment and disposal of collected material
- Capital Charges:
  - Taxes*
  - Insurance*
  - Interest*

Of the expenditure items shown above, only those denoted by an asterisk were considered in developing the cost estimates used in this chapter. Other factors, such as engineering studies, land acquisition, operating supply inventory, and structural modification, vary in cost from place to place and therefore were not included. Costs for the treatment and disposal of collected material, while also not included, are discussed in some detail in Section 6–8.

6.5.2 Capital Investment

The "installed cost" quoted by a manufacturer of air pollution equipment usually is based on his engineering study of the actual emission source. This cost includes three of the eight capital investment items—

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* Denotes cost items considered in this report.

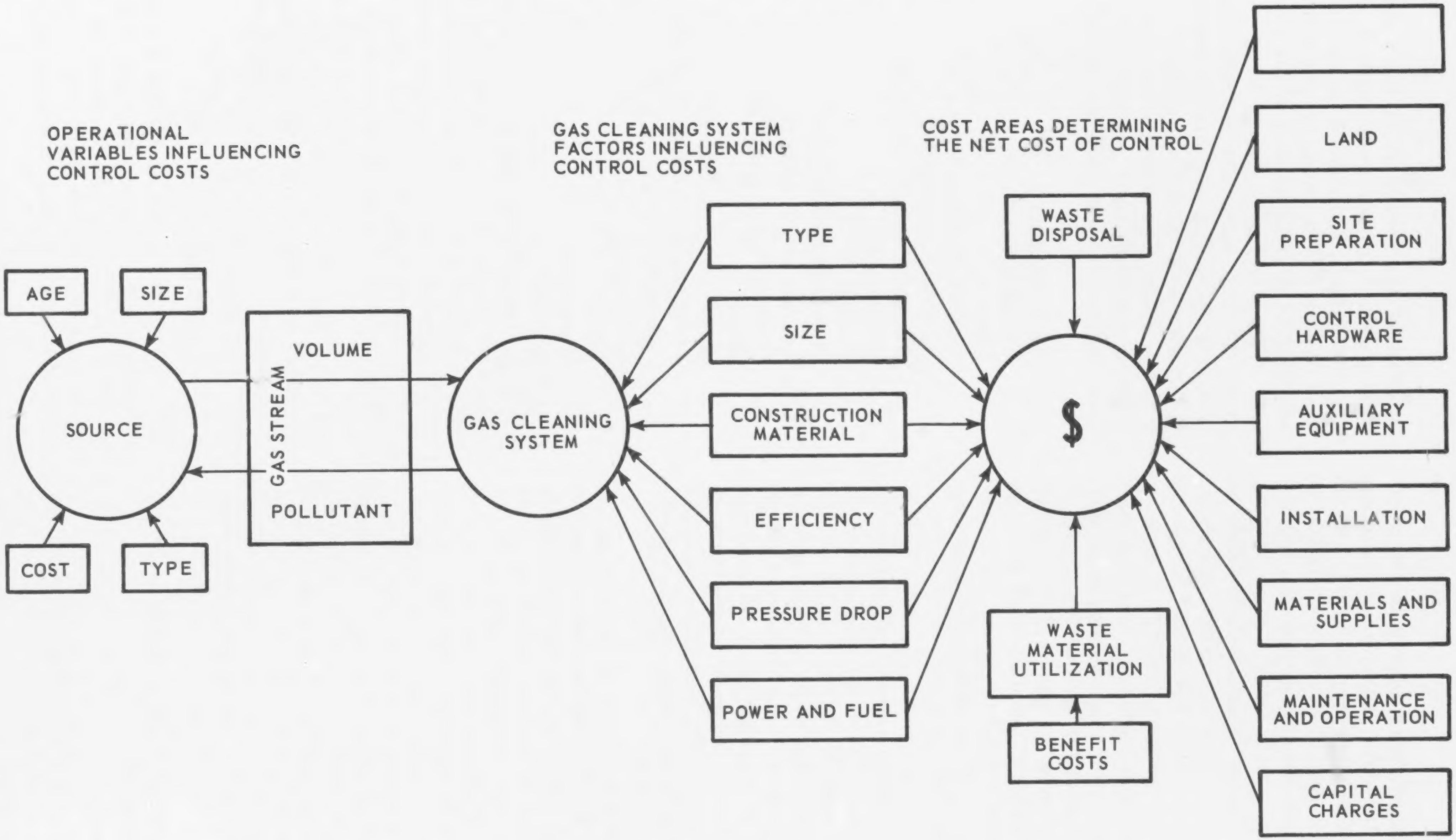
OPERATIONAL VARIABLES INFLUENCING CONTROL COSTS
GAS CLEANING SYSTEM FACTORS INFLUENCING CONTROL COSTS
COST AREAS DETERMINING THE NET COST OF CONTROL
AGE
SIZE
SOURCE
COST
TYPE
GAS STREAM
VOLUME
POLLUTANT
GAS CLEANING SYSTEM
TYPE
SIZE
CONSTRUCTION MATERIAL
EFFICIENCY
PRESSURE DROP
POWER AND FUEL
WASTE DISPOSAL
$
WASTE MATERIAL UTILIZATION
BENEFIT COSTS
LAND
SITE PREPARATION
CONTROL HARDWARE
AUXILIARY EQUIPMENT
INSTALLATION
MATERIALS AND SUPPLIES
MAINTENANCE AND OPERATION
CAPITAL CHARGES

FIGURE 6–4. Diagram of cost evaluation for a gas cleaning system.

Table 6-3.—TOTAL INSTALLATION COST FOR VARIOUS TYPES OF CONTROL DEVICES EXPRESSED AS A PERCENTAGE OF PURCHASE COSTS

Equipment type	Cost, percent			
	Low	Typical	High	Extreme high
Gravitational	33	67	100	-----
Dry centrifugal	35	50	100	400
Wet collector:				
Low, medium energy	50	100	200	400
High energy [a]	100	200	400	500
Electrostatic precipitators	40	70	100	400
Fabric filters	50	75	100	400
Afterburners	10	25	100	400

[a] High-energy wet collectors usually require more expensive fans and motors.

control hardware costs, auxiliary equipment costs, and costs for field installation.

The purchase cost curves that are shown in Section 6.7 illustrate the control hardware costs for various types of control equipment. These purchase costs are the amounts charged by manufacturer for equipment of standard construction materials. Basic control hardware includes built-in instrumentation and pumps. Purchase cost usually varies with the size and collection efficiency of the control device. The purchase costs plotted on the curves are typical for the efficiencies indicated, but these costs may vary ±20 percent from the values shown. Of course, equipment fabricated with special materials (e.g., stainless steel or ceramic coatings) for extremely high temperatures or corrosive gas streams may cost much more.

The remaining capital investment items, auxiliary equipment and installation costs, are aggregated together and referred to as "total installation costs." These costs are shown in Table 6-3, expressed as percentages of the purchase costs. These costs include a reasonable increment for the following items: (1) erection, (2) insulation material, (3) transportation of equipment, (4) site

Table 6-4.—CONDITIONS AFFECTING INSTALLED COST OF CONTROL DEVICES

Cost category	Low cost	High cost
Equipment transportation	Minimum distance; simple loading and unloading procedures.	Long distance; complex procedure for loading and unloading.
Plant age	Hardware designed as an integral part of new plant.	Hardware installed into confines of old plant requiring structural or process modification or alteration.
Available space	Vacant area for location of control system.	Little vacant space requires extensive steel support construction and site preparation.
Corrosiveness of gas	Noncorrosive gas	Acidic emissions requiring high alloy accessory equipment using special handling and construction techniques.
Complexity of startup	Simple startup, no extensive adjustment required.	Requires extensive adjustments; testing; considerable down time.
Instrumentation	Little required	Complex instrumentation required to assure reliability of control or constant monitoring of gas stream.
Guarantee on performance	None needed	Required to assure designed control efficiency.
Degree of assembly	Control hardware shipped completely assembled.	Control hardware to be assembled and erected in the field.
Degree of engineering design	Autonomous "package" control system.	Control system requiring extensive integration into process, insulation to correct temperature problem, noise abatement.
Utilities	Electricity, water, waste disposal facilities readily available.	Electrical and waste treatment facilities must be expanded, water supply must be developed or expanded.
Collected waste material handling.	No special treatment facilities or handling required.	Special treatment facilities and/or handling required.
Labor	Low wages in geographical area.	Overtime and/or high wages in geographical area.

preparation, (5) clarifiers and liquid treatment systems (for wet collectors), and (6) auxiliary equipment such as fans, ductwork, motors, and control instrumentation. The low values listed in the table are for minimal transportation and simple layout and installation of control devices. High values are for higher transportation cost and for difficult layout and installation problems. The extreme high values are for unusually complex installations on existing process equipment. Table 6–4 lists the major cost categories and related conditions that establish the installation cost range from low to high. The "installed cost" estimates reported in Section 6–7 are the sum of the purchase costs and the total installation costs.

6.5.3 Maintenance and Operation

The following sections describe the working equations for the operation and maintenance costs of various control devices. Numerical values for the variables expressed in these equations are found in Tables 6–5 and 6–6.

Table 6–5.—ANNUAL MAINTENANCE COSTS FOR ALL GENERIC TYPES OF CONTROL DEVICES

Generic type	Dollars per acfm		
	Low	Typical	High
Gravitational and dry centrifugal collectors	0.005	0.015	0.025
Wet collectors	0.02	0.04	0.06
Electrostatic precipitators:			
High voltage	0.01	0.02	0.03
Low voltage	0.005	0.014	0.02
Fabric filters	0.02	0.05	0.08
Afterburners:			
Direct flame	0.03 [a]	0.06 [b]	0.10 [b]
Catalytic	0.07	0.20	0.35

[a] Metal liner with outside insulation.
[b] Refractory lined.

6.5.3.1 General—The costs of operation and maintenance will vary widely because of different policies of control equipment users. This variance will depend on such factors as the quality and suitability of the control equipment, the user's understanding of its operation, and his vigilance in maintaining it. Maintenance and operation usually are very difficult to define and assess, but often

Table 6–6.—MISCELLANEOUS COST AND ENGINEERING FACTORS

[Fan efficiency = 60 percent; Pump efficiency = 50 percent]

Power cost, dollars/kw-hr [a]

	Low	Typical	High
All devices	0.005	0.011	0.020

Hours of operation, 8760 hours per year, 24 hr/day ×365 days/yr = 8760

	Low	Medium	High
Power requirements vs efficiency for high-voltage electrostatic precipitators, 10^{-3} kw/acfm	0.19	0.26	0.40

	Low	High
Power requirements vs efficiency for low-voltage electrostatic precipitators (10^{-3} kw/acfm)	0.015	0.040

	Low	Typical	High
Liquor cost in 10^{-3} dollars per gallon per hour (for wet system)—Wet scrubber (make-up liquor requirements, 0.0005 gal/hr-acfm)	0.35	0.50	1.00

Power requirements

	Low efficiency	Medium efficiency	High efficiency
"Scrubbing" (contact) power, horsepower/acfm	0.0013	0.0035	0.015

Scrubber liquor data

	Low	Typical	High
Liquor circulation rate, gal/acfm	0.001	0.008	0.020
Minimum head requirements, feet water	*1	30	60

Pressure drop through equipment, inches of water

Generic type	Low	Typical	High
Dry centrifugal collector	—	2–3	4
Fabric filter	2–3	4–5	6–8
Afterburners	0.5	1.0	2
Electrostatic precipitators and gravitational collectors	0.1	0.5	1

[a] Based on national average of large consumers.
*1 psig = 2.3 ft water.

may be a significant portion of the overall cost of controlling air pollutant emissions. Although the combined operating and maintenance costs may be as low as 10 percent of the annualized total cost for a gravitational settling chamber, for example, they may be as high as 90 percent of the total annualized cost for a high-efficiency wet collector.

Maintenance cost is the expenditure required to sustain the operation of a control device at its designed efficiency with a scheduled maintenance program and necessary replacement of any defective parts. On an annual basis, maintenance cost in the following equations is assumed proportional to the capacity of the device in acfm. Table 6–5 shows annual maintenance cost factors for all types of particulate control devices. Simple, low-efficiency control devices have low maintenance costs; complex, high-efficiency devices have high maintenance costs.

Annual operating costs is the expense of operating a control device at its designed collection efficiency. This cost depends on the following factors: (1) the gas volume cleaned, (2) the pressure drop across the system, (3) the operating time, (4) the consumption and cost of electricity, (5) the mechanical efficiency of the fan, and (6) the scrubbing liquor consumption and costs (where applicable).

6.5.3.2 Gravitational and Centrifugal Mechanical Collectors—In general, the only significant cost for operating mechanical collectors is the electric power cost, which varies with the unit size and the pressure drop. Since pressure drop in gravitational collectors is low, operational costs associated with these units are considered to be insignificant. Maintenance cost includes the costs of servicing the fan motor, replacing any lining worn by abrasion, and, for multiclone collectors, flushing the clogged small diameter tubes.

Cost equation—The theoretical annual cost (G) of operation and maintenance for centrifugal collectors can be expressed as follows:

$$G = S\left[\frac{0.7457\ PHK}{6356E} + M\right] \qquad (1)$$

where:

S = design capacity of the collector, acfm
P = pressure drop inches of water (see Table 6–6)
E = fan efficiency, assumed to be 60 percent (expressed as 0.6)
0.7457 = a constant (1 horsepower = 0.7457 kilowatt)
H = annual operating time (assumed 8760 hours)
K = power cost, dollars per kilowatt-hour (see Table 6–6)
M = maintenance cost, dollars per acfm (see Table 6–5)

For computational purposes the cost formula can be simplified as follows:

$$G = S[195.5 \times 10^{-6}\ PHK + M] \qquad (2)$$

6.5.3.3 Wet Collectors—The operating costs for a wet collector power and scrubbing liquor costs. Power costs vary with equipment size, liquor circulation rate, and pressure drop. Liquor consumption varies with equipment size and stack gas temperature. Maintenance includes servicing the fan or compressor motor, servicing the pump, replacing worn linings, cleaning piping, and any necessary chemical treatment of the liquor in the circulation system.

Cost equation—the theoretical annual cost (G) of operation and maintenance for wet collectors can be expressed as follows:

$$G = S\left[0.7457\ HK\left(\frac{P}{6356E} + \frac{Qg}{1722F} + \frac{Qh}{3960F}\right) + WHL + M\right] \qquad (3)$$

where:

S = design capacity of the wet collector, acfm
0.7457 = a constant (1 horsepower = 0.7457 kilowatts)
H = annual operating time (assumed 8760 hours)
K = power costs, dollars per kilowatt-hour
P = pressure drop across fan, inches of water (see Table 6–6)
Q = liquor circulation, gallons per acfm (see Table 6–6)
g = liquor pressure at the collector, psig (see Table 6–6)

h = physical height liquor is pumped in circulation system, feet (see Table 6–6)
W = make-up liquor consumption, gallons per acfm (see Table 6–6)
L = liquor cost, dollars per gallon (see Table 6–6)
M = maintenance cost, dollars per acfm see Table 6–5)
E = fan efficiency, assumed to be 60 percent (expressed as 0.60)
F = pump efficiency, assumed to be 50 percent (expressed as 0.50)

The above equation can be simplified according to Semrau's total "contacting power" concept.[6] Semrau shows that efficiency is proportional to the total energy input to meet fan and nozzle power requirements. The scrubbing (contact) power factors in Table 6–6 were calculated from typical performance data listed in manufacturers' brochures. These factors are in general agreement with data reported by Semrau. Using Semrau's concept the equation for operating cost can be simplified as follows:

$$G = S\left[0.7457\ HK\left(Z + \frac{Qh}{1980}\right) + WHL + M\right]$$

where Z = contact power (i.e., total power input required for collection efficiency), horsepower per acfm (see Table 6–6). It is a combination of:

1. fan horsepower per acfm

$$\left(= \frac{P}{6356\ E}\right), \text{ and}$$

2. pump horsepower per acfm

$$\left(= \frac{Qg}{1722\ F}\ \ \text{the power to atomize water through a nozzle}\right)$$

The pump horsepower, Qh/1980, required to provide pressure head is not included in the contact power requirements.

6.5.3.4 Electrostatic Precipitators — The only operating cost considered in the operation of electrostatic precipitators is the power cost for ionizing the gas and operating the fan. As the pressure drop across the equipment is usually less than ½ inch of water, the cost of operating the fan is assumed to be negligible. The power cost varies with the efficiency and the size of the equipment.

Maintenance usually requires the services of an engineer or highly-trained operator, in addition to regular maintenance personnel. Maintenance includes servicing fans and replacing damaged wires and rectifiers.

Cost equation—The theoretical annual cost (G) for operation and maintenance of electrostatic precipitators is as follows:

$$G = S\ [JHK + M] \qquad \textbf{(4)}$$

where
S = design capacity of the electrostatic precipitator, acfm
J = power requirements, kilowatts per acfm (see Table 6–6)
H = annual operating time (assumed 8760 hours)
K = power cost, dollars per kilowatt-hour (see Table 6–6)
M = maintenance cost, dollars per acfm (see Table 6–5)

6.5.3.5 Fabric Filters—Operating costs for fabric filters include power costs for operating the fan and the bag cleaning device. These costs vary directly with size of equipment and the pressure drop. Maintenance costs include costs for servicing the fan and shaking mechanism, emptying the hoppers, and replacing the worn bags.

Cost equation—The theoretical annual cost (G) for operation and maintenance of fabric filters is as follows:

$$G = S\left[\frac{0.7457}{6356E}\ PHK + M\right] \qquad \textbf{(5)}$$

where:
S = design capacity of the fabric filter, acfm
P = pressure drop, inches of water (see Table 6–6)
E = fan efficiency, which is assumed to be 60 percent (expressed as 0.60)
0.7457 = a constant (1 horsepower = 0.7457 kilowatt)
H = annual operating time (assumed 8760 hours)
K = power cost, dollars per kilowatt-hour (see Table 6–6)
M = maintenance cost, dollars per acfm (see Table 6–5)

Table 6-7. HOURLY FUEL COSTS

Device	Temperature, °F		Δ Temperature, °F	Fuel cost,[a] dollars/acfm-hr
	Inlet	Outlet		
Direct flame (DF)	380	1400	1020	$0.00057
DF with heat exchanger	1000	1400	400	0.00023
Catalytic afterburner (CAB)	380	900	520	0.00028
CAB with heat exchanger	650	900	250	0.00014

[a] These figures include the cost of heating an additional 50 percent excess air. It is assumed there is no heat content in the material or pollutant being consumed.

For computational purposes, the cost formula can be simplified as follows:

$$G = S[195.5 \times 10^{-6}\ PHK + M] \qquad (6)$$

6.5.3.6 Afterburners—The major operating cost item for afterburners is fuel. Fuel requirements are a direct function of the gas volume, the enthalpy of the gas, and the difference between inlet and outlet gas temperatures. For most applications, the inlet gas temperature at the source ranges from 300° to 400° F. Outlet temperatures may vary from 1200° to 1500° F for direct flame afterburners and from 730° to 1200° F for catalytic afterburners.[2] The use of heat exchangers may bring about a 50 percent reduction in the temperature difference.[7,8] Table 6–7 lists hourly fuel costs based on a natural gas cost of $0.60 per million Btu. No credit was given for heat of combustion of particulate or other matter. These costs were developed from enthalpies (heat content) of the process gas at given temperatures.[9] Maintenance includes servicing the fan, repairing the refractory lining, washing and rinsing the catalyst, and rejuvenating the catalyst.[10]

The equation for calculating the operation and maintenance costs (G) is as follows:

$$G = S\left[\frac{0.7457}{6356}\ \frac{PHK}{E} + HF + M\right] \qquad (7)$$

where:

S = design capacity of the afterburner, acfm

P = pressure drop, inches of water (see Table 6–6)

E = fan efficiency, assumed to be 60 percent (expressed as 0.60)

0.7457 = a constant (1 horsepower = 0.7457 kilowatt)

H = annual operating time (assumed 8760 hours)

K = power cost, dollars per kilowatt-hour (see Table 6–6)

F = fuel cost, dollars per acfm per hour (see Table 6–7)

M = maintenance cost, dollars per acfm (see Table 6–5)

For computational purposes, the cost formula is simplified as follows:

$$G = S[195.5 \times 10^{-6}\ PHK + HF + M] \quad (8)$$

6.5.4 Capital Charges

Capital charge includes overhead expenses such as taxes, insurance, and interest incurred in the operation of a control device. Such costs frequently lose specific identity because of internal accounting practices. It is possible, however, by reasonable assumptions, to include capital charges in the annualized cost of control.

6.5.5 Annualization of Costs

Annualized capital costs are estimated by depreciating the capital investment (total installed cost) over the expected life of the control equipment and adding the capital charges (taxes, interest, and insurance). Adding the recurring maintenance and operation costs to this figure gives a total annualized cost of control. Total annualized cost estimates are shown in Section 6.7.

6.5.6 Assumptions in Annualized Control Cost Elements

Annualized control costs will differ from installation to installation and from region to region, and certain simplifying assumptions have been necessary to develop the cost figures of this section. If more information for a given location is available, it is desirable to substitute this for the assumptions used here.

6.5.6.1 Annualized Capital Cost Assumptions—The simplifying assumptions for computing the total annualized capital cost are as follows:

1. Purchase and installation costs are depreciated over 15 years, a period assumed to be a feasible economic life for control devices.
2. The straight line method of depreciation (6⅔ percent per year) is used because it is the most common method used in accounting practices. This method has the simplicity of a constant annual writeoff.
3. Other costs called capital charges—which include interest, taxes, insurance, and other miscellaneous costs—are assumed to be equal to the amount of depreciation, or 6⅔ percent of the initial capital cost of the control equipment installed. Therefore, depreciation plus these other annual charges amount to 13⅓ percent of the initial capital cost of the equipment.

6.5.6.2 Operating Cost Assumptions—The following assumptions were taken into account for computing operation and maintenance costs.

1. Power costs included in annual operating expense reflect electricity used by all systems directly associated with the control equipment. Electrical power requirements are computed on a constant usage basis at a specified gas volume.
2. For wet collectors, it is assumed that the liquor is recirculated in a closed system. Liquor consumption consists of the makeup liquor which must be added from time to time. Stack gas temperature influences the rate of liquor loss; this influence is partially accounted for by assuming a constant loss per cubic foot of stack gas volume. This assumption is necessary because of the extremely wide range of stack gas temperatures.
3. The costs for electricity and water are computed on the marginal rate classes for each size user, which assumes that any additional consumption will be priced at the lowest rate-highest volume class available. Except where specifically indicated, the typical values for the pressure drop and cost of electricity (see Table 6–7) were assumed in all control cost calculations and illustrations.
4. The disposal cost and/or recovered value of collected effluents are not included in the operating cost calculations because of cost differences from process to process. Disposal cost figures for several major industrial categories are reported in Section 6.8.

6.5.6.3 Maintenance Cost Assumptions—It is assumed that a user of control equipment establishes a preventive (scheduled) maintenance program and carries it out to maintain equipment at its designed collection efficiency. Further, it is assumed that unscheduled maintenance, such as replacement of defective parts, is undertaken as required. The cost incurred for equipment modification or repair due to an operational accident is not included.

6.6 METHOD FOR ESTIMATING ANNUAL COST OF CONTROL FOR A SPECIFIC SOURCE

6.6.1 General

As previously indicated, it is beyond the scope of this report to identify and assess the cost of control for a specific source. Such assessments can, however, be calculated by applying the steps outlined below.

6.6.2 Procedure

The following procedure can be used to determine the expected cost of control for any source.

Step 1. Describe the source (including characteristics of the process), the characteristics and consumption of fuel for combustion, and the total number of hours in operation annually. Emissions can be determined by making stack gas tests or can be estimated by making calculations using the emission factors.

Step 2. Select the applicable types of control equipment. Figure 6–1 illustrates what must be considered in selecting the optimum type of control equipment.

Step 3. Specify pressure drops, efficiencies, construction material, energy and fuel requirements, and size limitations for the selected control equipment, taking into account any existing equipment.

Step 4. Determine the gas flow in acfm at the point of collector location. For wet collectors, this would be the water saturated gas volume. This should be done by taking measurements at maximum operating conditions.

Step 5. Determine the estimated total purchase cost for the specific selected device (curves found in Section 6.7) at the required gas volume and control efficiency. For fabric filters, select the proper filter medium for the process.

Step 6. Multiply the cost found in step 5 by the low, typical, and high installation cost factors (Table 6–3), and add the result to the estimated total purchase cost to obtain the corresponding low, typical, and high total installed costs. Conditions affecting the cost of installation are listed in Table 6–4.

Step 7. Calculate the total annual capital cost as follows:

annualized capital cost
= depreciation + capital charges
= 0.133 × total investment cost*

Step 8. Compute the cost of electricity, maintenance, and liquor consumption.

Step 9. Compute low, medium, and high operating and maintenance costs from the appropriate formulas:

Dry centrifugal collectors

$$G = S[195.5 \times 10^{-6}\ PHK + M]$$

Wet scrubbers

$$G = S\left[0.7457\ HK\left(Z + \frac{Qh}{1980}\right) + WHL + M\right]$$

Electrostatic precipitator

$$G = S[JHK + M]$$

Fabric filters

$$G = S[195.5 \times 10^{-6}\ PHK + M]$$

Afterburners

$$G = S[195.5 \times 10^{-6}\ PHK + M + HF]$$

where:

G = theoretical value for operating and maintenance costs
S = the design capacity of the collection device, acfm
P = pressure drop of the gas, inches of water
H = annual operating time
K = power costs, dollars per kilowatt-hour
Q = liquor circulation, gallons per acfm
h = physical height that liquor is pumped in circulation system, feet
Z = total power input required for scrubbing efficiency, horsepower per acfm
M = maintenance cost, dollars per acfm
W = liquor consumption, gallons per hour per acfm
L = cost of liquor, dollars per gallon
J = power requirement, kilowatts per acfm based on efficiency
F = fuel cost, dollars per hour per acfm

Step 10. Add the typical annualized capital cost to the typical operating and maintenance cost to yield the estimated total annualized cost of control.

Step 11. Because the above calculation is a point estimate, the range of costs should be investigated. For this, a variance is calculated and applied to the total estimated annual cost. The low cost variance (V_l) and high cost variance (V_h) of an equipment combination can be computed by using the square root of the sum of the squares. The formulas for these variances are as follows:

$$V_l = \sqrt{(C_m - C_l)^2 + (G_m - G_l)^2}$$

$$V_h = \sqrt{(C_h - C_m)^2 + (G_h - G_m)^2}$$

where:

C_l, C_m, and C_h are the low, typical, and high annual capital cost estimates, respectively, and G_l, and G_m, and G_h are the low, typical, and high operation and maintenance cost estimates. These formulas are taken from the usual definition of the standard error of a linear combination of statistically independent variables. They permit computation of the most probable, rather than the extreme, range of costs.

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* Based on the assumptions in Section 6.5.6.1.

Step 12. The high cost variance (V_h) is added to the total estimated annual cost to yield the high cost limit.

Step 13. The low cost variance (V_l) is subtracted from this total estimated annual cost to yield the low cost limit.

6.6.3 Sample Calculations

The following calculations illustrate the method used to determine the total estimated annual cost of control. The following example shows the estimation of annualized cost for a 60,000 cfm, 90 percent (medium efficiency) wet collector.

Step 1. Annual operating time = 8760 hours (H)

Step 2. Wet collector (given)

Step 3. 90 percent efficiency (given)
Scrubbing power required—0.0035 horsepower per acfm (Z)

Step 4. Actual gas flow = 60,000 acfm (given)

Step 5. Purchase cost = $17,000 (from Section 6.7.4 for wet collectors)

Step 6. Installation factors from Table 6-3 are 50 percent, 100 percent and 200 percent

Installation factor	50%	100%	200%
Installation cost	$8,500	$17,000	$34,000
Purchase cost	$17,000	$17,000	$17,000
Total capital cost	$25,500	$34,000	$51,000

Step 7. 0.133 × [Total capital cost] = annual capital cost (C)

$C_l = 0.133 \times \$25{,}500 = \$3400$

$C_m = 0.133 \times \$34{,}000 = \$4530$

$C_h = 0.133 \times \$51{,}000 = \$6800$

Step 8. Power cost, dollars/kw-hr (K)

Low	Typical	High
0.005	0.011	0.020

Maintenance cost, dollars/acfm, (M)

Low	Typical	High
0.02	0.04	0.06

Liquor cost, 10^{-3} dollars/gal, (L)

Low	Typical	High
0.35	0.50	1.00

Head required for circulation in system, feet, (h)

Low	Typical	High
1	30	60

Liquor circulation, gallons per acfm, (Q)

Low	Typical	High
0.001	0.008	0.020

Makeup liquor rate, 10^{-3} gal/hr-acfm, (W) = 0.5

Step 9. Using the following formula to determine annual operating cost (G),

$$G = S\left[\left(Z + \frac{Qh}{1980}\right)(0.7457\ HK) + WHL + M\right]$$

the low, typical and high operating and maintenance costs are as follows:

$G_l = \$8200 \qquad G_m = \$18{,}100 \qquad G_h = \$35{,}900$

Step 10. From the steps 7 and 9,

$$C_m = \$4530 \qquad G_m = \$18{,}100$$

Then, the total estimated annual cost is as follows:

$$C_m + G_m = \$22{,}600$$

Step 11. Using the square root of the sum of the squares of the differences, the high and low cost variances are as follows:

$V_l = \sqrt{(C_m - C_l)^2 + (G_m - G_l)^2}$

$V_l = \sqrt{(4530 - 3400)^2 + (18{,}100 - 8200)^2}$

$V_l = \$10{,}000$

$V_h = \sqrt{(C_h - C_m)^2 + (G_h - G_m)^2}$

$V_h = \sqrt{(6800 - 4530)^2 + (35{,}900 - 18{,}100)^2}$

$V_h = \$17{,}900$

Step 12. From Step 10, the total estimated annual cost = $22,600

From Step 11, $V_l = \$10{,}000$

Low cost limit = $22,600 − $10,000 = $12,600

Step 13. Total estimated annual cost = \$22,600

From Step 11, V_h = \$17,900

High cost limit = \$22,600 + \$17,900 = \$40,500

Step 14. The amount of particulate matter emitted may be calculated if the inlet conditions are known.

6.6.4 Annualized Cost Variation

The previous section illustrated the probable high and low cost limits for a single installation, taking into account the variation in cost for installation, maintenance, and operation. To compute the annualized cost for a given emission reduction system, one must take into account four variables: (1) collection efficiency of the system, (2) cost of installing the system, (3) cost of operation, and (4) maintenance cost. A more complete summary of the range of total annualized costs is shown in Table 6–8 for a 60,000 acfm wet collector. This table illustrates cost figures for 81 possible combinations of each of the four variables, with each variable taking on three independent values—low, typical, and high. It is constructed by the procedure outlined in Steps 1 through 10 in the previous section. The constants for computing these values are taken from Tables 6–5 and 6–6. Table 6–8 shows that a low-efficiency 60,000 acfm wet collector with low installation, maintenance, and operation costs will cost approximately \$6100 per year to operate (extreme upper left hand corner). The most efficient (99 percent efficiency) wet collector, according to the table, will cost as high as \$137,400 per year to operate. The most likely costs for efficiencies of 75 percent, 90 percent, and 99 percent are \$11,300; \$22,700; and \$74,500, respectively. The type of data shown in Table 6–8 is useful in developing cost-effectiveness relationships. Note that this table does not show the variances, V_l and V_h; these should be used only when the probable cost limits are desired.

6.7 COST CURVES BY EQUIPMENT TYPE

6.7.1 General

For the convenience of those who may use the cost information described in this chapter, the following sections contain a series of control cost curves (see Figures 6–5 through 6–24). For each type of control equipment, a series of curves is presented: (1) purchase cost curves, (2) installed cost curves, and (3) annualized cost curves.

The estimated purchase cost curves show

Table 6–8.—ILLUSTRATIVE PRESENTATION OF ANNUAL COSTS OF CONTROL FOR 60,000 acfm WET SCRUBBER (dollars)

[e]	[d]	E_l = 75 percent [a, b]			E_m = 90 percent			E_h = 99 percent		
		I_l [c]	I_m	I_h	I_l	I_m	I_h	I_l	I_m	I_h
	M_l	6,100	6,800	8,100	11,800	13,000	15,200	35,500	37,800	42,300
O_l	M_m	7,300	8,000	9,300	13,000	14,200	16,400	36,700	39,000	43,500
	M_h	8,500	9,200	10,500	14,200	15,400	17,600	37,900	40,200	44,700
	M_l	9,500	10,100	11,500	20,300	21,500	23,700	71,100	73,300	77,900
O_m	M_m	10,700	11,300	12,700	21,500	22,700	24,900	72,300	74,500	79,100
	M_h	11,900	12,500	13,900	22,700	23,900	26,100	73,500	75,700	80,300
	M_l	18,300	18,900	20,300	36,900	38,100	40,300	128,200	130,500	135,000
O_h	M_m	19,500	20,100	21,500	38,100	39,300	41,500	129,400	131,700	136,200
	M_h	20,700	21,300	22,700	39,300	40,500	42,700	130,600	132,900	137,400

[a] E = efficiency factor.

[b] Subscripts l, m, and h indicate low, medium, and high ranges, respectively.

[c] I = installation factor.

[d] M = maintenance factor.

[e] O = operating factor.

NOTE: A similar table can be generated to show the various control costs for any type of control equipment by specifying operating conditions and calculating each entry. This procedure provides complete information to aid in the assessment of existing controls or other control alternatives.

the dollar amounts charged by manufacturers for basic control equipment, exclusive of transportation charges to the installation site. This basic control equipment includes built-in auxiliary parts of the control unit, such as instrumentation and solution pumps. The installed cost curves include the purchase costs, additional auxiliary equipment costs, and installation costs, as described in Section 6.5.2. The annualized cost curves include elements discussed in Section 6.5.3 through 6.5.6. The assumptions, sources of data, and the limitations used to develop this information are discussed in Sections 6.3 and 6.4.

6.7.2 Gravitational Collectors

In computing the cost of gravity collectors, three collection efficiencies were considered. These efficiencies were based on the assumption of essentially complete removal of 87-micron, 50-micron, and 25-micron particles, and are designated as low, medium, and high efficiencies, respectively. The low and medium efficiency collectors are simple expansion chambers, and the high efficiency collector is a multiple-tray settling chamber, commonly called a Howard separator.

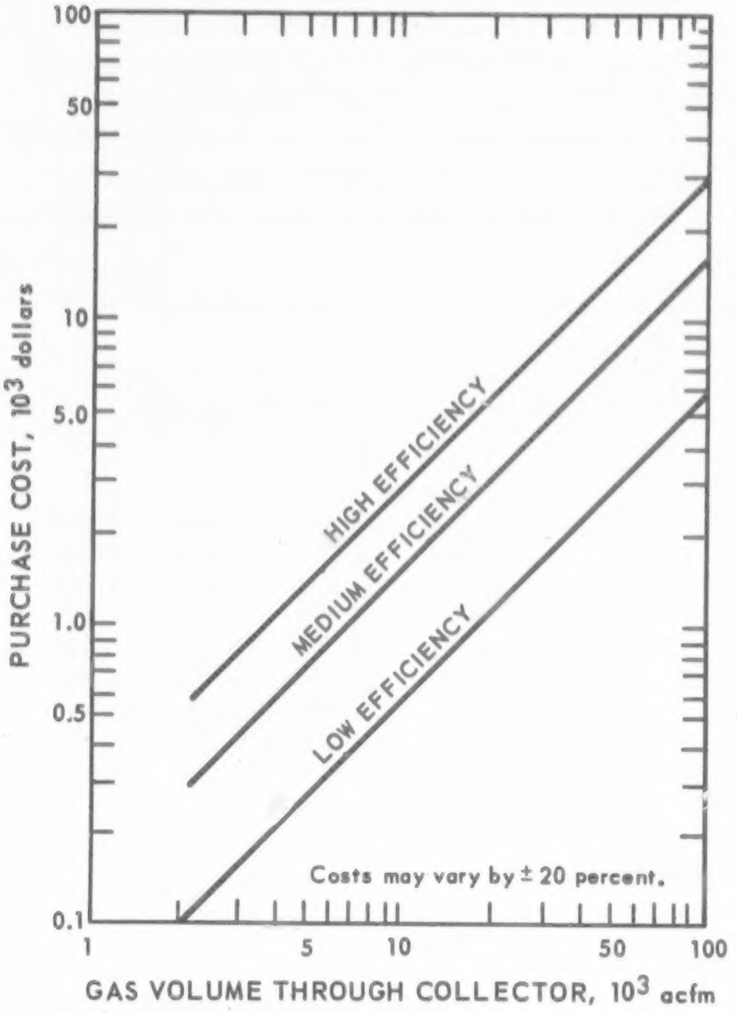

FIGURE 6–5. Purchase cost of gravitational collectors.

In actual operation, the collection efficiency for a gravitational collector depends on the particle size distribution. In cleaning the flue gas from a stoker-fired coal furnace, for example, low-, medium-, and high-efficiency collectors would have particle removal efficiencies of approximately 64 percent, 75 percent, and 88 percent, respectively. In cleaning the flue gas from a pulverized coal furnace, these same collectors, because of the smaller-sized particles emitted by the combustion unit, would have approximate efficiencies of 21 percent, 34 percent, and 56 percent, respectively.

The purchase costs of gravitational collectors are shown for three different efficiencies in Figure 6–5. These are approximate costs for typical installations. If it were necessary to include insulation or a corrosion-resistant lining, the costs would be higher. The total installed cost was also calculated for each efficiency and is shown in Figure 6–6. The total installed cost is the sum of the purchase and installation costs. The installation costs were assumed to range from 33 percent to 100 percent of the purchase cost (see Table 6–3), and this range results in a cost band for each efficiency, as shown in the figure. No annualized cost curves are presented for these collectors because operation and maintenance costs, other than for removal and disposal of collected material, usually are negligible, except where corrosion may be a problem. Section 6.8 provides specific information on the disposal of collected material.

6.7.3 Dry Centrifugal Collectors

The costs of purchasing, installing, and operating mechanical centrifugal collectors are given in Figures 6–7, 6–8, and 6–9 respectively. The curves in these figures show costs for collectors that operate at nominal efficiencies of 50 percent, 70 percent, and 95 percent (see Section 6.4). Costs are plotted for equipment sizes ranging from 10,000 to 1,000,000 acfm. The assumptions used in

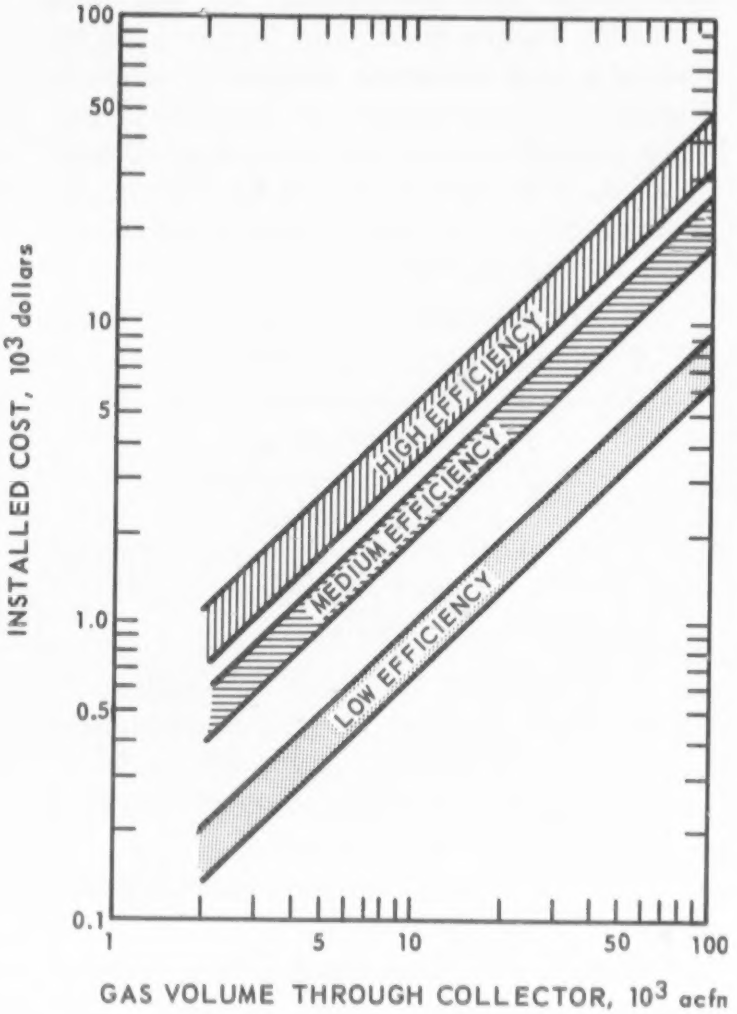

FIGURE 6-6. Installed cost of gravitational collectors.

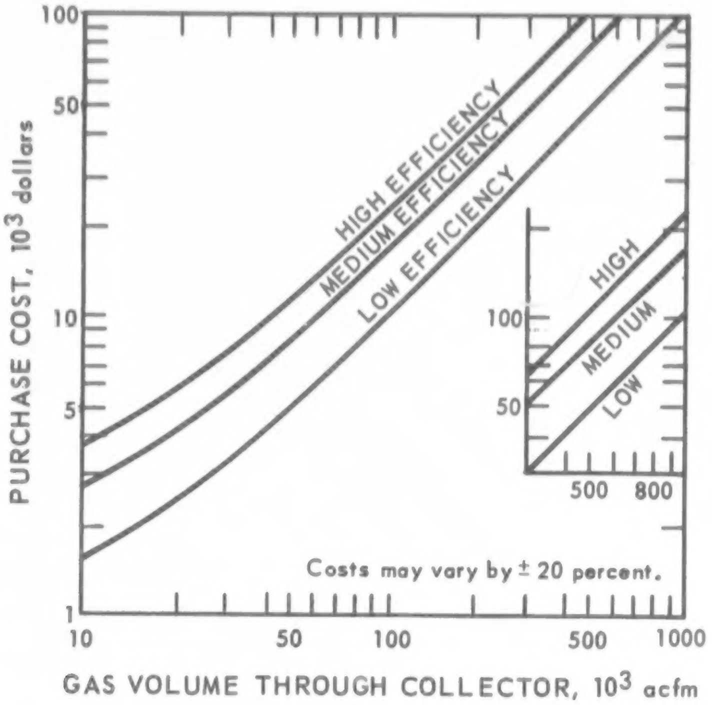

FIGURE 6-7. Purchase cost of dry centrifugal collectors.

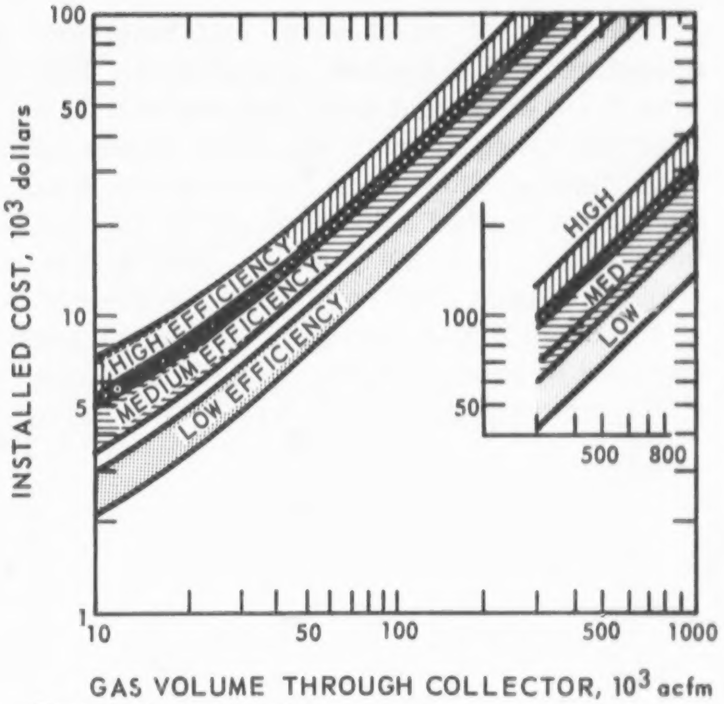

FIGURE 6-8. Installed cost of dry centrifugal collectors.

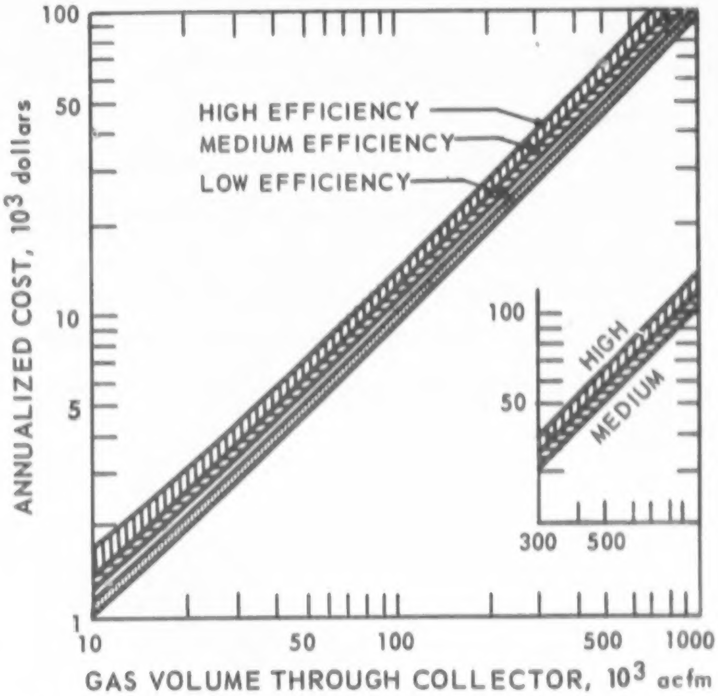

FIGURE 6-9. Annualized cost of operation of dry centrifugal collectors.

calculating annual operation and maintenance costs for dry centrifugal collectors are as follows:

1. Annual operating time = 8760 hours
2. Collector pressure drop = 3 inches of water
3. Power cost = \$0.011/kw-hr
4. Maintenance cost = \$0.015/acfm

6.7.4 Wet Collectors

The costs of purchasing, installing, and operating wet collectors are given in Figures 6–10, 6–11, and 6–12, respectively, as a function of equipment size. The curves in these figures show costs for collectors that operate at normal efficiencies of 75 percent, 90 percent, and 99 percent (see Section 6.4). The basic hardware costs for medium and high collection efficiency equipment are reported by manufacturers to lie in the same cost range and both appear on the same curve in Figure 6–10. The higher installed cost of a high collection efficiency system in Figure 6–11 results from the need for larger, more expensive auxiliary equipment (based on Table 6–3). The assumptions used in calculating annual operating and maintenance costs for wet collectors are as follows:

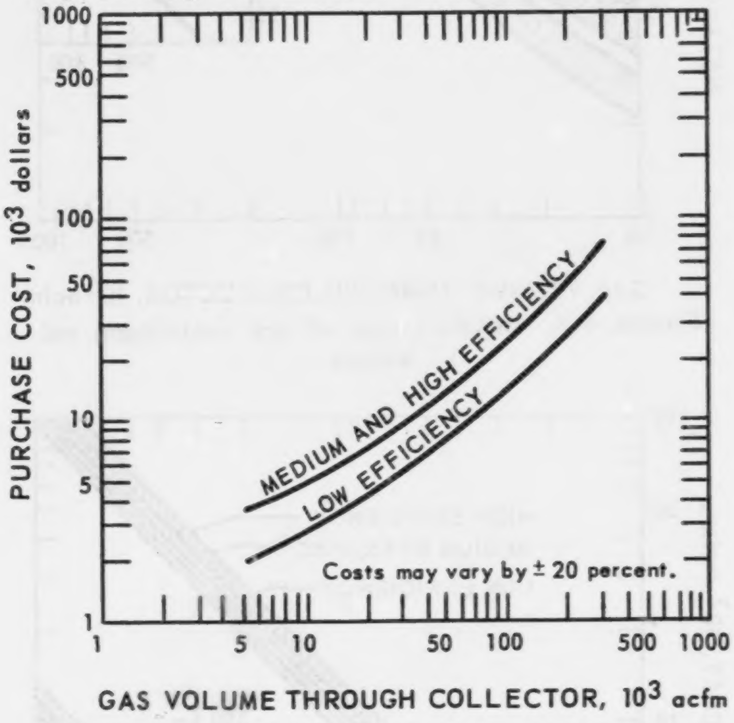

FIGURE 6–10. Purchase cost of wet collectors.

1. Annual operating time = 8760 hours
2. Contact power requirements:
   - 0.0013 horsepower/acfm for 75 percent efficiency
   - 0.0035 horsepower/acfm for 90 percent efficiency
   - 0.015 horsepower/acfm for 99 percent efficiency
3. Power cost = \$0.011/kw-hr
4. Maintenance cost = \$0.04/acfm
5. Head required for liquor circulation in collection system = 30 feet
6. Liquor circulation = 0.008 gallon/acfm
7. Liquor consumption = 0.0005 gallon/hour-acfm
8. Liquor cost = \$0.0005/gallon

6.7.5 High-Voltage Electrostatic Precipitators

The costs of purchasing, installing, and operating high-voltage electrostatic precipi-

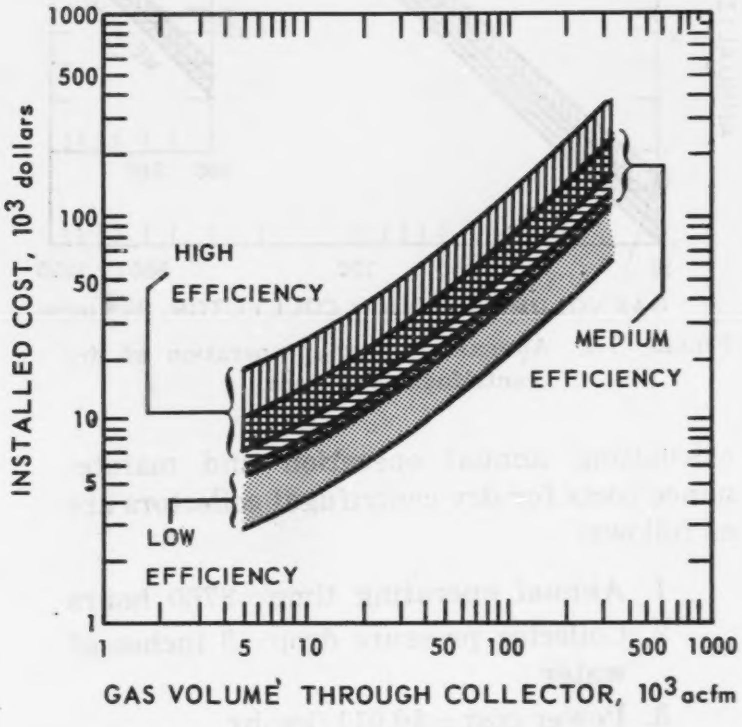

FIGURE 6–11. Installed cost of wet collectors.

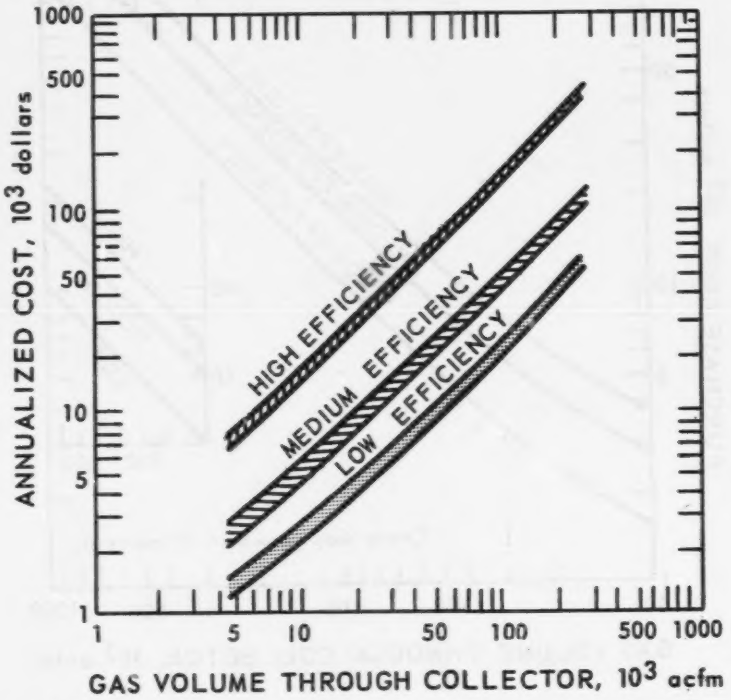

FIGURE 6–12. Annualized cost of operation of wet collectors.

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tators are given in Figures 6–13, 6–14, and 6–15, respectively. The curves in these figures show costs for collectors that operate at nominal efficiencies of 90 percent, 95 percent, and 99.5 percent. These costs are plotted for equipment sizes ranging from 20,000 to 1,000,000 acfm. The assumptions used in calculating annual operation and maintenance costs for high-voltage electrostatic precipitators are as follows:

1. Annual operating time = 8760 hours
2. Electrical power requirements:
    0.00019 kw/acfm for low efficiency
    0.00026 kw/acfm for medium efficiency
    0.00034 kw/acfm for high efficiency
3. Power cost = \$0.011/kw-hr
4. Maintenance cost = \$0.02/acfm

6.7.6 Low-Voltage Electrostatic Precipitators

The curves in Figures 6–16, 6–17, and 6–18 indicate purchase cost, installed cost, and operation cost of low-voltage electrostatic precipitators for low and high collection efficiencies based on design gas velocities of 150 and 125 feet per minute, respectively. Packaged modular low-voltage precipitators with flow rates of less than 1500 acfm are used to collect oil mist from machining operations. Purchase cost of such a unit usually is less than \$1200. The assumptions used in calculating annual operation and maintenance costs for low-voltage electrostatic precipitators are as follows:

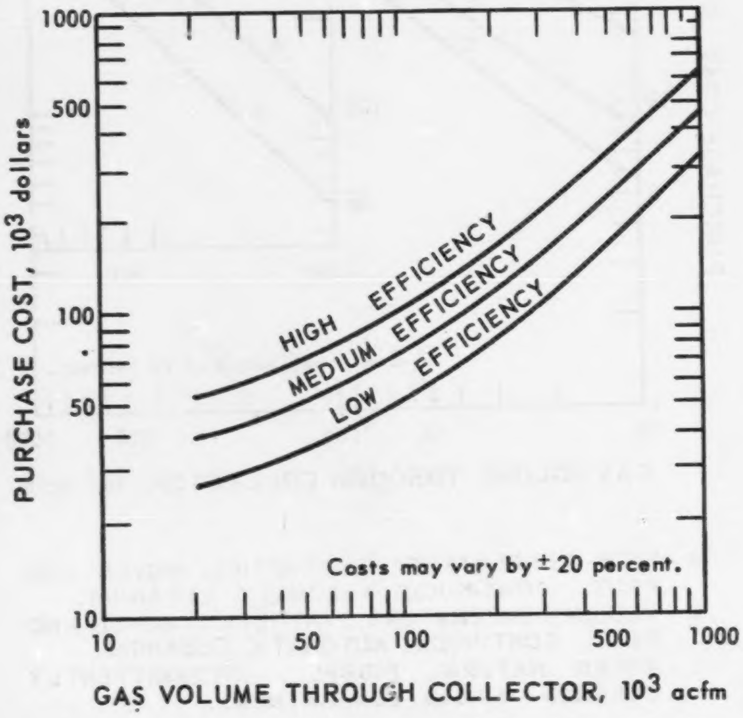


FIGURE 6–13. Purchase cost of high-voltage electrostatic precipitators.

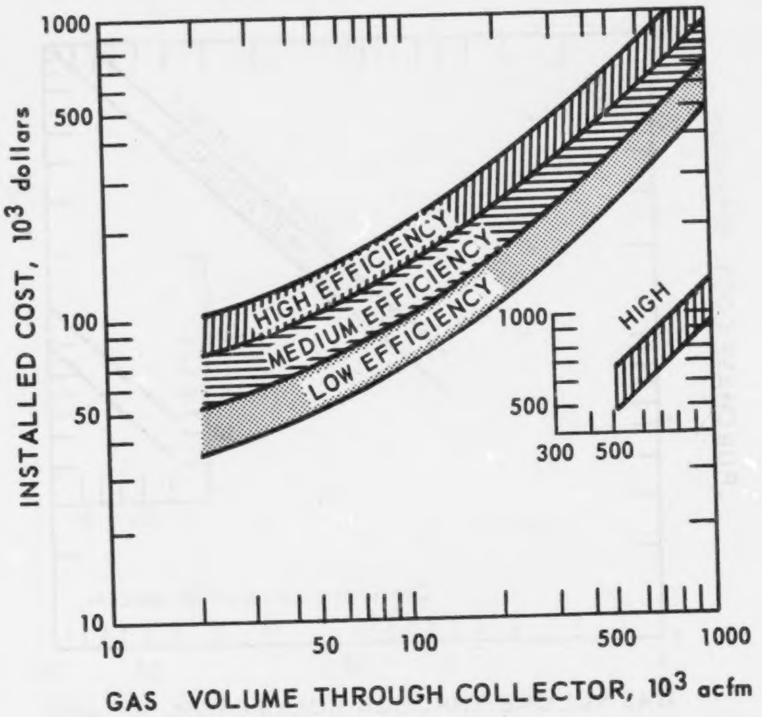


FIGURE 6–14. Installed cost of high-voltage electrostatic precipitators.

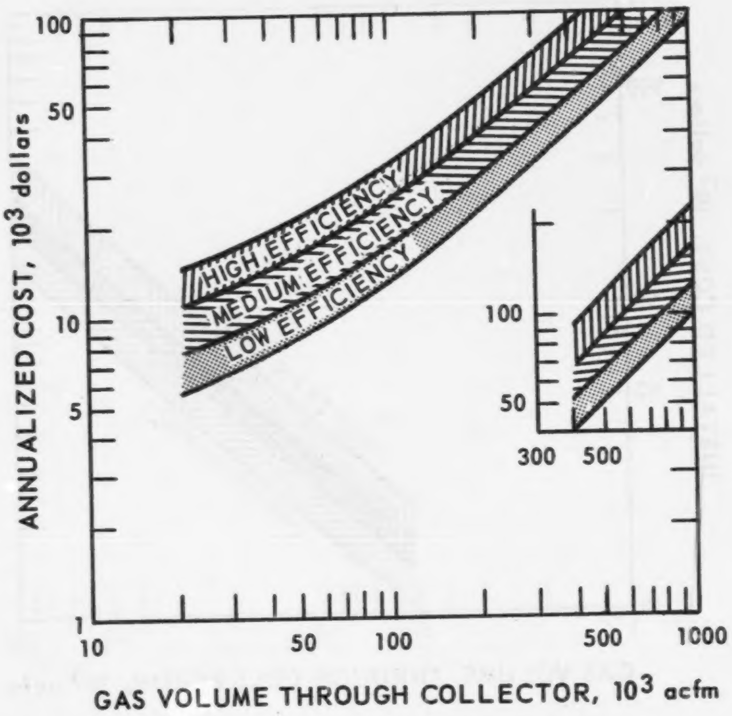


FIGURE 6–15. Annualized cost of operation of high-voltage electrostatic precipitators.

1. Annual operating time = 8760 hours
2. Electrical power requirements:
    0.000015 kw/acfm for low efficiency
    0.000040 kw/acfm for high efficiency
3. Power cost = \$0.011/kw-hr
4. Maintenance cost = \$0.02/acfm

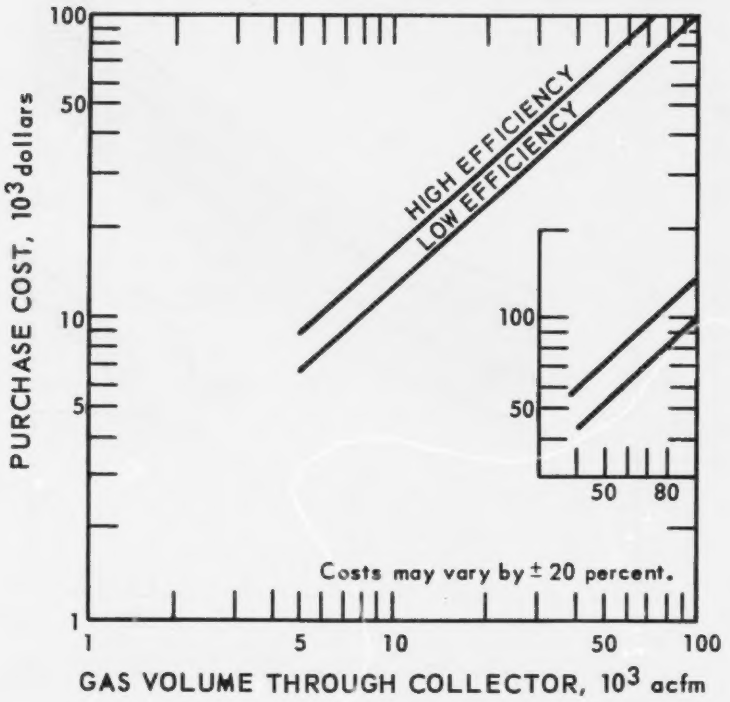


FIGURE 6–16. Purchase cost of low-voltage electrostatic precipitators.

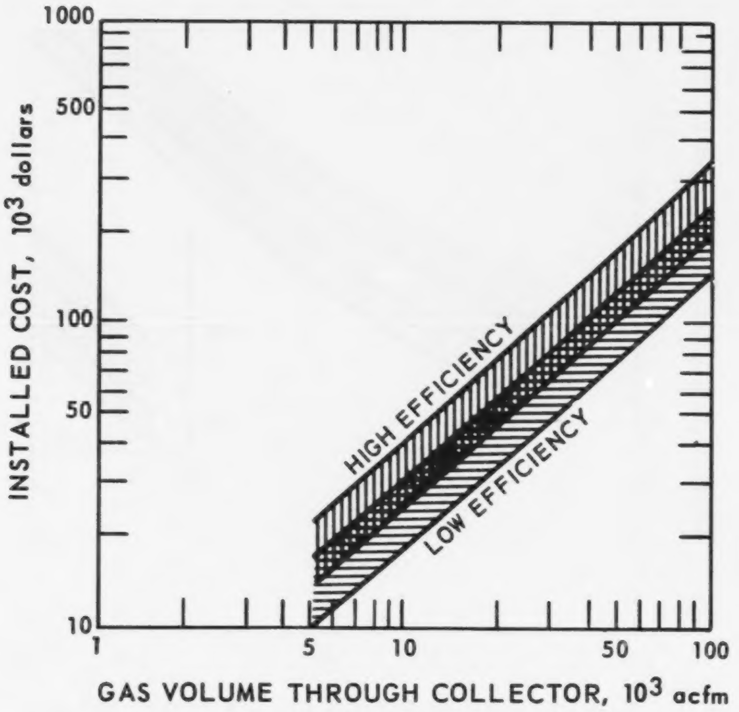


FIGURE 6–17. Installed cost of low-voltage electrostatic precipitators.

6.7.7 Fabric Filters

Figures 6–19, 6–20, and 6–21 show purchase cost, installed cost, and annualized cost of control for three different types of filters. Each of the three filters is designed with

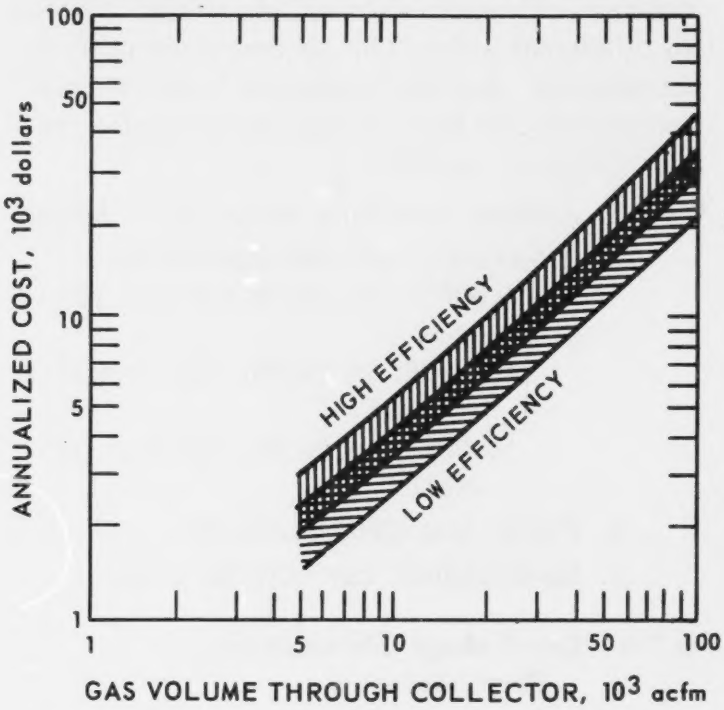
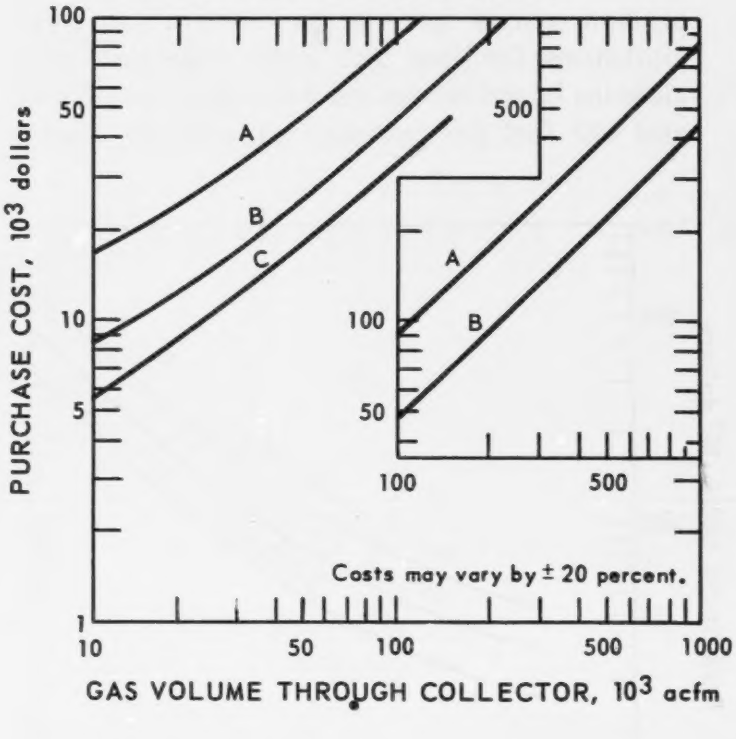


FIGURE 6–18. Annualized cost of operation of low-voltage electrostatic precipitators.



A - HIGH-TEMPERATURE SYNTHETICS, WOVEN AND FELT. CONTINUOUS AUTOMATIC CLEANING.
B - MEDIUM-TEMPERATURE SYNTHETICS, WOVEN AND FELT. CONTINUOUS AUTOMATIC CLEANING.
C - WOVEN NATURAL FIBERS. INTERMITTENTLY CLEANED - SINGLE COMPARTMENT.

FIGURE 6–19. Purchase cost of fabric filters.

about the same efficiency—99.9 percent. Costs are plotted for equipment sizes ranging from 10,000 to 1,000,000 acfm.

The control cost curves represent the following different types of filter installations:

1. Curve A represents a fabric filter installation with high-temperature synthetic woven fibers (including fiberglass) and felted fibers cleaned continuously and automatically.
2. Curve B represents an installation using medium-temperature synthetic woven and felted fibers, such as Orlon or Dacron, cleaned continuously and automatically.
3. Curve C is the least expensive installation. Woven natural fibers are used in a single compartment. Filters are intermittently cleaned. This equipment is rarely designed for processes handling over 150,000 acfm.

These control cost curves do not include data for furnace hoods, ventilation ductwork and pre-coolers that may appear only in certain installations. The assumptions for calculating operating and maintenance costs are as follows:

1. Annual operating time=8760 hours
2. Pressure drop of the gas through the three types of fabric filters=4 inches of water
3. Power cost=\$0.05/acfm
4. Maintenance cost=\$0.05/acfm

6.7.8 Afterburners

Afterburners are separated into four categories: (1) direct flame, (2) catalytic, (3) direct flame with heat recovery, and (4) catalytic with heat recovery. Equipment and installation costs were obtained from both the literature and manufacturers of afterburners. Sufficient data were received on catalytic afterburners to define the narrow purchase cost range shown in Figure 6–22. The figure shows that purchase costs of direct flame afterburners have a wider range than those of catalytic afterburners.

Figure 6–23 shows the installation costs for afterburners. Heat exchangers are con-

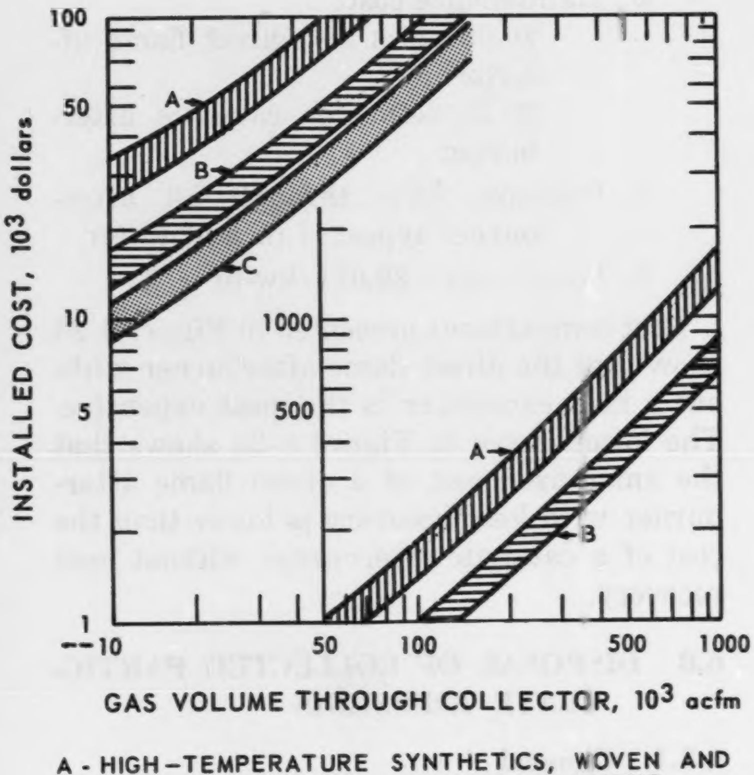


Figure 6–20. Installed cost of fabric filters.

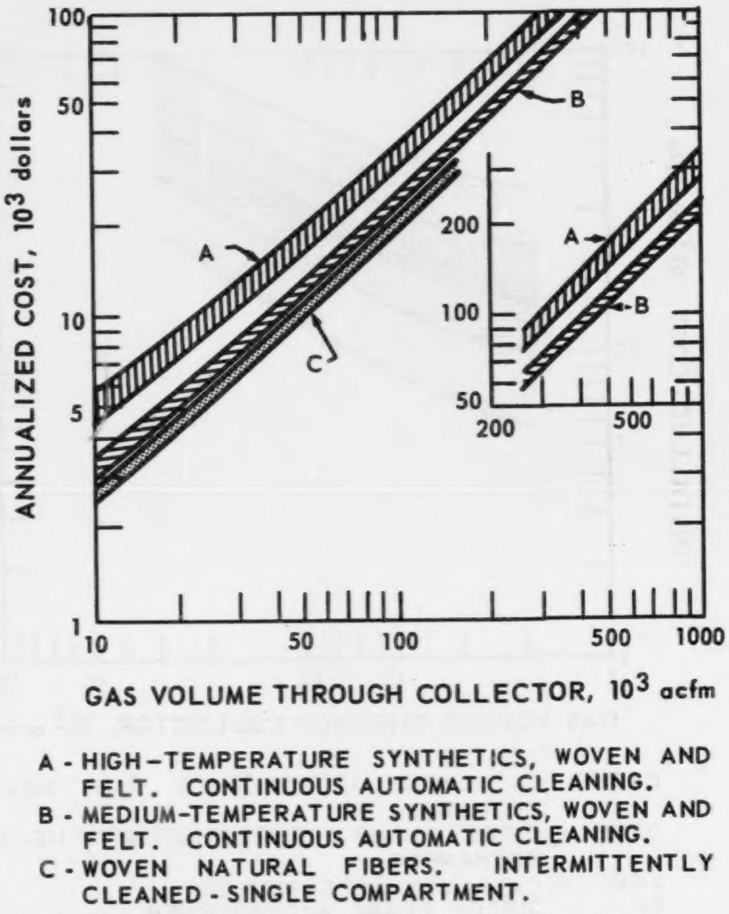


Figure 6–21. Annualized cost of operation of fabric filters.

sidered accessory equipment and appear as part of the installation cost. Installation costs may range from 10 percent to 100 percent of the purchase costs, although in some situations they may be as high as 400 percent. Differences in installation costs are due to the differences in burner locations relative to the emission source, and differences in structural supports, ductwork, and foundations. Installation costs for the addition of equipment to existing plant facilities will be higher than similar costs for new plants. Other factors accounting for different installation fees are the degree of instrumentation required, engineering fees in manufacturers' bids, startup tests and adjustments, heat exchangers, auxiliary fans, and utilities. The assumptions for calculating operation and maintenance costs are as follows:

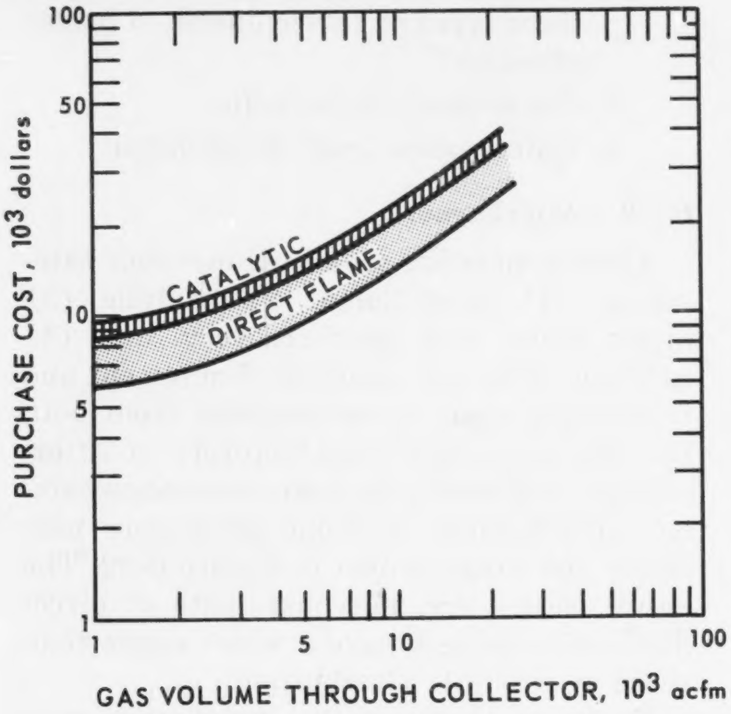


Figure 6–22. Purchase cost of afterburners.

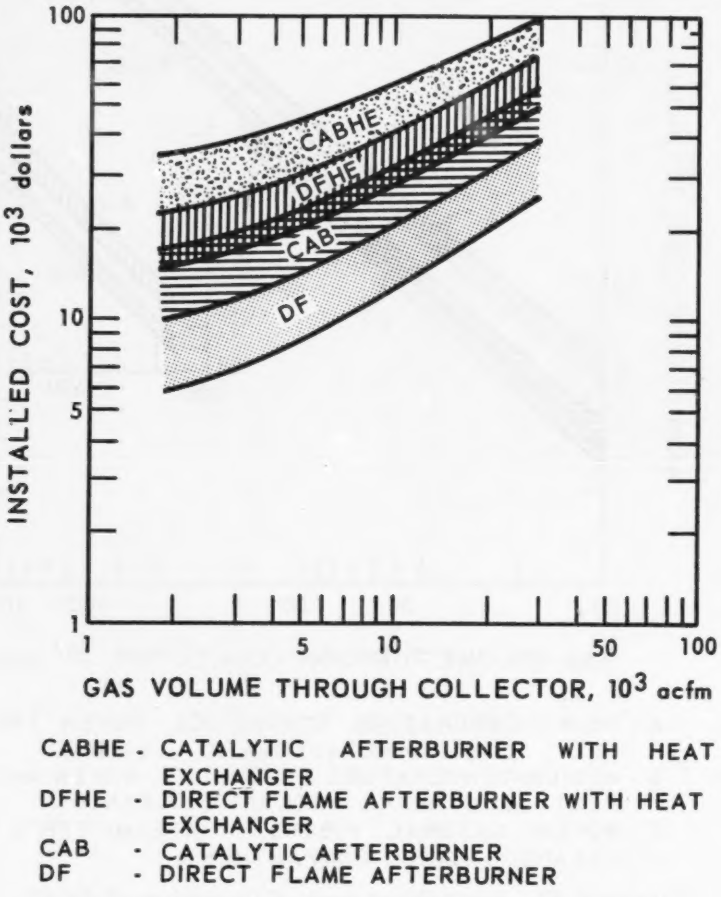


Figure 6–23. Installed cost of afterburners.

1. Annual operating time = 8760 hours
2. Fuel cost:
    - \$0.57/1000 acfm-hour for direct flame afterburner with no heat recovery
    - \$0.23/1000 acfm-hour for direct flame afterburner with heat recovery \$0.28/1000 acfm-hour for catalytic afterburner with no heat recovery
    - \$0.14/1000 acfm-hour for catalytic afterburner with heat recovery
3. Maintenance cost:
    - \$0.06/acfm for direct flame afterburner
    - \$0.20/acfm for catalytic afterburner
4. Pressure drop through all afterburner types = 1 inch of water
5. Power cost = \$0.011/kw-hr

Cost comparisons presented in Figure 6–24 show that the direct flame afterburner without a heat exchanger is the most expensive. The lower curve in Figure 6–24 shows that the annualized cost of a direct flame afterburner with heat recovery is lower than the cost of a catalytic afterburner without heat recovery.

6.8 DISPOSAL OF COLLECTED PARTICULATE EMISSIONS

6.8.1 General

The installation of any pollution control system designed to collect particulate matter demands a decision regarding the disposal of the collected particulate material.

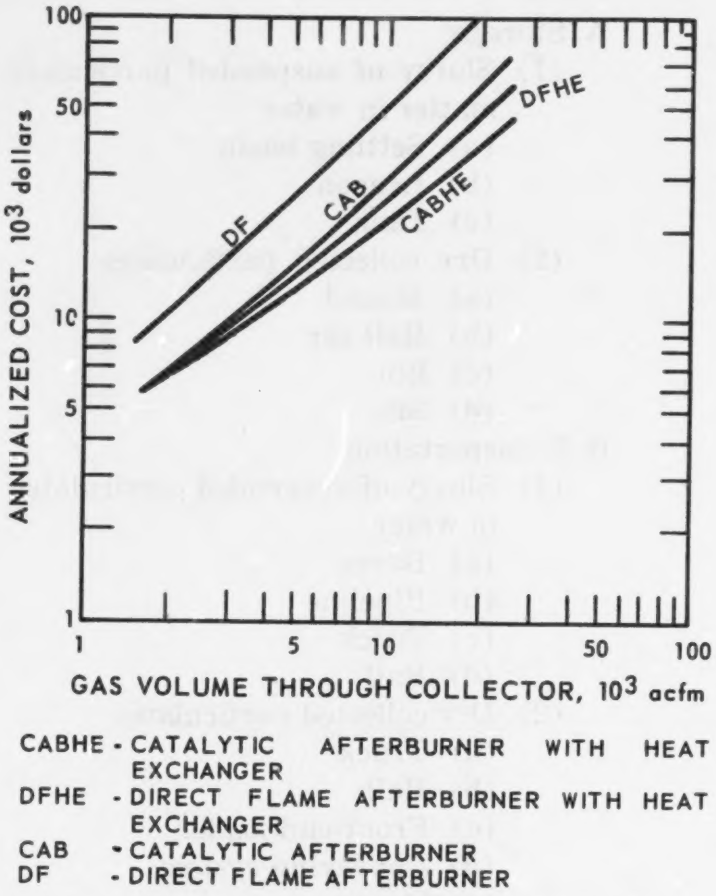


FIGURE 6–24. Annualized cost of operation of afterburners.

This section discusses the relevant factors and illustrates the economic consequences of disposal of the collected material.

In the past, pollution control equipment often was installed either to reduce a severe nuisance or to recover valuable material. Such equipment not only prevented valuable material from escaping to the atmosphere but also reduced costly cleaning of the plant grounds and facilities.

As industrial plants become more crowded together and as the public desires a higher quality of air, more emphasis will be placed on intensive control activities. This emphasis will increase the demand for more effective air pollution control. Generally, most air pollution control systems collect material that has little economic worth.

Basically, the alternatives for handling collected particulate material are as follows:

1. Return the material to the process.
2. Sell the material directly as collected.
3. Convert the material to a saleable product.
4. Discard the material in the most economical manner.

The process of selecting an alternative should take into account the following questions:

1. Can the material be used within the company?
2. Is there a profitable market for the material?
3. What is the most economical method of disposal?
4. Is there land available for a landfill?
5. Is there a source of water available for:
   a. a wet pipeline system
   b. disposal at sea
   c. transportation by barge
6. Is there space available for a settling basin or filtering system?
7. Is there process-related equipment presently available for transporting or treating the collected material?
8. Is there access to a municipal waste treatment system?
9. Can technology and/or markets be developed for utilization of the waste material?

6.8.2 Elements of Disposal Systems

After examining feasible solutions to the disposal problem, the least costly alternative that is most compatible with other operating factors in the plant should be chosen. The decision should result from consideration of each of the four functional elements of the disposal system described below and their relationships to the manufacturing process.

1. *Temporary storage, which allows gathering sufficient quantities of the collected material to make final disposal more economical.* The unit cost of disposal usually is lower for greater quantities. Temporary storage may be convenient at many points in the overall disposal scheme, such as in the hopper or settling chamber of a pollution control device, or in a silo some distance from the plant.
2. *Transportation that moves the collected material from the particulate control device to some location where disposal is relatively economical.* In most cases, transportation displaces

the material to a location where accumulation minimizes any potential interference with plant activities. Any single disposal system may require more than one method of transporting the material. For example, a conveyor system may be used at the control device, a truck may be used to transport the material to a landfill area, and a bulldozer may be used to push it to its final disposal location.

3. *Treatment that changes physical and/or chemical characteristics for easier disposal.* Such treatment may simplify operations and reduce costs for handling and disposal of wastes. Frequently, for easier transport, particulate matter is made into a slurry by adding water to it. This permits the use of a pipeline, which is often the most economical method for transporting wastes over long distances. Slurries from wet scrubbing pollution control systems frequently are treated in an opposite manner: the water is removed and the particulate matter is concentrated by filtration or sedimentation. This permits the ultimate disposal of a solid waste, rather than a sludge or a slurry. The method of treatment should be selected with a view to minimizing contamination of the environment. Examples of such treatment methods are the wetting of fine dust to prevent air pollution, the neutralization and filtration of slurries to prevent contamination of receiving waters, and the proper burial of solid material in a sanitary landfill.
4. *Final disposition, which pertains to discarding the unusable material.* Material which cannot be sold, converted, or re-used ultimately can be discarded in landfills; or sometimes it can be disposed of in lagoons or the sea.

The following list shows some examples of the four functional elements for both wet and dry disposal systems:

A. Storage
  (1) Slurry of suspended particulate matter in water
    (a) Settling basin
    (b) Lagoon
    (c) Tank
  (2) Dry collected particulates
    (a) Mound
    (b) Rail car
    (c) Bin
    (d) Silo
B. Transportation
  (1) Slurry of suspended particulates in water
    (a) Barge
    (b) Pipeline
    (c) Truck
    (d) Rail
  (2) Dry collected particulates
    (a) Truck
    (b) Rail
    (c) Front-end loader
    (d) Conveying system
    (e) Barge
C. Treatment
  (1) Slurry of suspended particulate in water [11]
    (a) Sedimentation
    (b) Filtration
    (c) Flotation
    (d) Thickening; wet combustion
    (e) Lagoons and drying beds
    (f) Vacuum filtration
    (g) Centrifugation; incineration
    (h) Neutralization
  (2) Dry collected material
    (a) Compressing
    (b) Wetting
D. Final Disposition
  (1) Landfill
    (a) Public or private disposal sites
    (b) Quarry
    (c) Evacuated coal mine
  (2) Lagoon
  (3) Dump at sea

The arrangement of these elements in an overall disposal scheme is shown in Figure 6–25. This flow diagram shows the movement of the collected material through various stages toward final disposal.

Environmental factors such as space, utili-

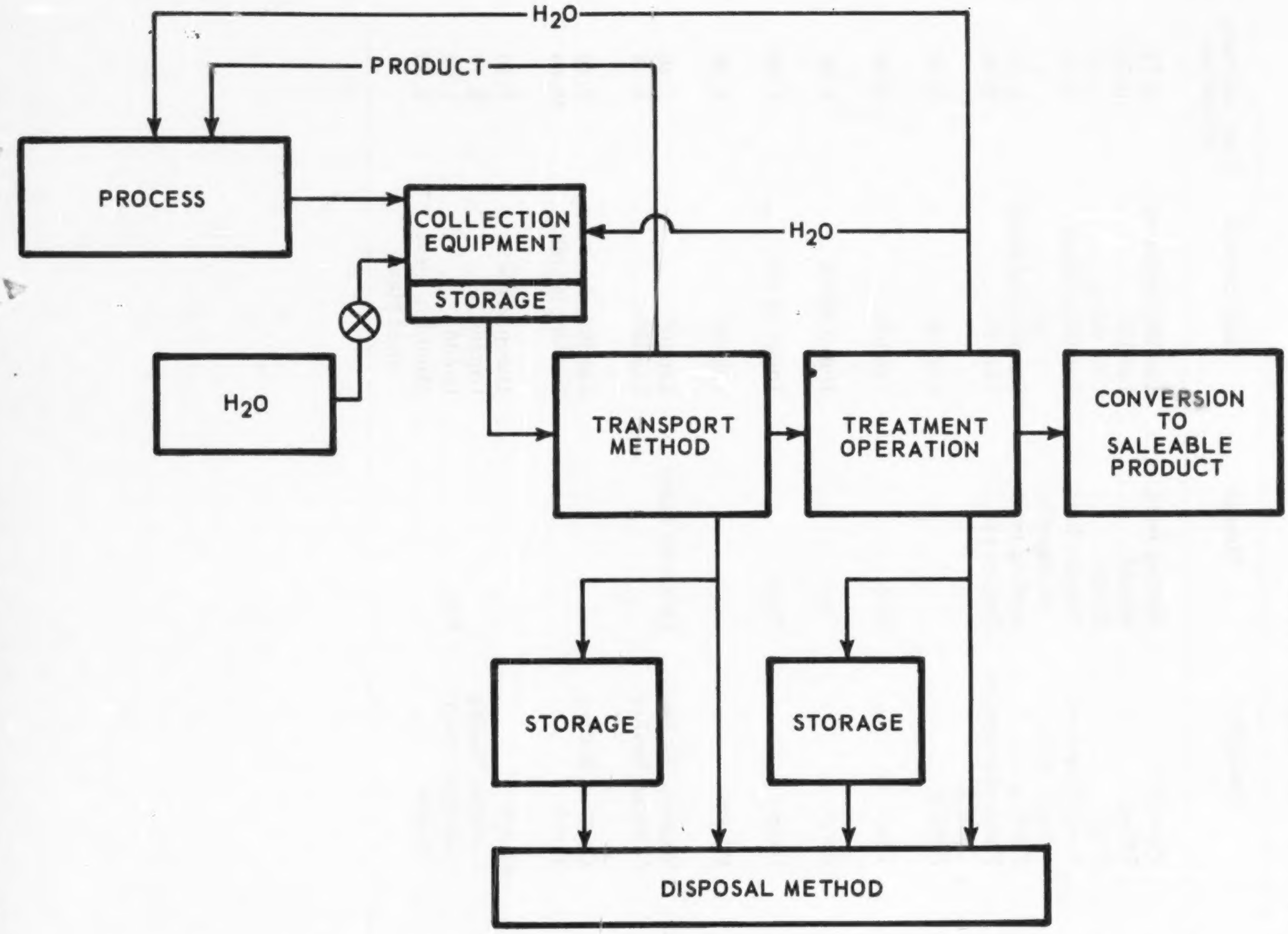


FIGURE 6-25. Flow diagram for disposal of collected particulate material from air pollution control equipment.

ties, disposal facilities, and the desired form of collected waste material usually have an important bearing on the selection of a disposal system compatible with a specific type of particulate pollution control equipment. Therefore, a specific type of particulate pollution control equipment may not always call for the same waste disposal system.

6.8.3 Disposal Cost for Discarded Material

Table 6-9 describes various disposal systems and the related costs within specific industries. Each system listed is specifically designed to cope with the disposal problem and available facilities of the individual plant shown. Therefore, drawing general conclusions about the relative costs of systems listed in the table would be erroneous. The disposal costs shown include capital charges and costs for labor and material. The disposal cost per ton will be higher the smaller the quantity of material, because capital charges for investment in facilities will remain the same regardless of quantity.

Fly ash, a residue from the combustion of coal and residual oil, probably is the most common material collected in emission control systems. An estimated 20 million tons of fly ash was produced in the United States in 1965. Only 3 percent of this total was sold as a marketable product.[12] If the cost for discarding the remaining 97 percent of the fly ash as unusable waste were $1.00 per ton or more, this would represent a total cost of $20 million or more. Based on the data in Table 6-9, a cost of $1.00 per ton is a typical unit cost.

In certain situations, the disposal cost of fly ash can be a major portion of the total annualized cost for a complete pollution control system (including disposal facilities). For example, the disposal costs can be as

Table 6-9.—COSTS OF SPECIFIC DISPOSAL SYSTEMS

Industry	Collected material	Treatment	Transport	Storage	Final disposal	Cost estimate, dollars/ton
Power generation	Fly ash	Sedimentation	Pipeline	Settling pond	Landfill (Sediment)	0.75
Power generation	Fly ash		Truck	Mound	Landfill	0.55
Power generation	Fly ash		Truck	Mound	City dump	1.10
Power generation	Fly ash	Form pellets	Vacuum system, truck, barge.	Transfer bins, storage silo.	Landfill or dump at sea.	2.00
Power generation	Fly ash	Form slurry	Pipeline	Settling pond	Landfill (Sediment)	2.00
Power generation	Fly ash	Wetted	Pneumatic pipeline truck.	Storage silo	Landfill	2.00
Power generation for chemical plant.	Fly ash	Sedimentation	Pipeline		Lagoon	1.60
Power generation for chemical plant.	Fly ash		Truck	Silos	Landfill	0.90
Chemical		Slurry (100,000 gal/day).	Barge	Tank	Dump at sea	3.00
Chemical	Weak acid (large volume).		Barge	Tank	Dump at sea	1.00
Power generation for pulp and paper.	Fly ash	Sedimentation	Pipeline		Lagoon	2.30
Gray iron foundry	Cupola dust	Water clarification	Sediment by truck	Dempster dump	Landfill	1.40
Petroleum refining	Non-dewatered sludge.		Contract hauling		Landfill	4.75
Petroleum refining	Dewatered sludge		Contract hauling		Landfill	2.50
Petroleum refining	Sludge, filter cake, oily solids.		Truck		In-plant landfill	20.00
Petroleum refining	Oily solids		Barge		Dump at sea	7.50
Petroleum refining	Catalyst fines		Contract hauling		Landfill	2.75
Portland cement	Waste dust	Slight wetting	Conveyor, truck	Bins	Landfill	1.05
Soaps and detergents	Suspended solids		Pipeline		Municipal treatment plant.	2.50

high as 80 percent of the total annualized cost for an emission control system with older electrostatic precipitators which are no longer depreciated. The disposal cost still can be as high as 50 percent for similar systems with newly installed electrostatic precipitators, which usually have high depreciation charges.

Table 6–10 shows a summary of fly ash disposal costs for material collected from electrostatic precipitators and mechanical collectors installed in electric utilities and is taken from a recent survey.[13] This survey analyzed the costs of disposal, the sales, and the uses of fly ash collected by 54 electric utilities and reported an average disposal cost of $0.74 per ton. Analysis of the data for individual utilities revealed that disposal cost is partly a function of geographical location. The average disposal cost per ton in the heavily-populated East is higher than that reported elsewhere.

Table 6–10.—COST OF ASH DISPOSAL BY ELECTRIC UTILITIES

Type and collection method	Disposal costs, dollars/ton		
	Low	Medium	High
Fly ash (mechanical collector)	$0.15	$0.59	$1.67
Fly ash (electrostatic precipitator)	0.12	0.77	1.74
Bottom ash	0.15	1.04	4.76

6.8.4 Return of Collected Material to the Process

In some process operations, collected material is sufficiently valuable to warrant its return to the process. In these situations, the value of the recovered material can partially or wholly pay for the collection equipment. In many applications, however, the cost for the high efficiency control systems necessary to achieve desired ambient air quality will be greater than the revenue returned for recovery of the material collected. This is illustrated by the hypothetical example in Figure 6–26.

The figure shows a linear relationship between collection efficiency and value of material recovered. It also shows a curvilinear relationship between collection efficiency and related equipment costs. Up to the break-even point D (which corresponds to an efficiency of about 97 percent), the recovery value of material collected is greater than the cost to achieve the recovery. Equipment designed for efficiencies greater than 97 percent, according to the curve, would have a higher cost than the potential recovery value.

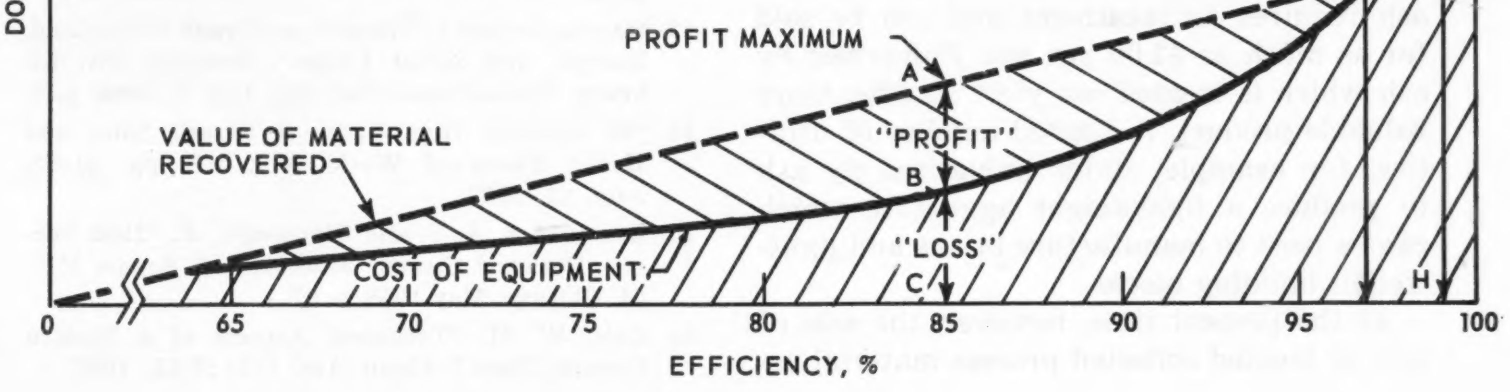


FIGURE 6–26. Theoretical effect of dust value on control cost.

If profit were the only control incentive, 85 percent collection efficiency would achieve the maximum profit, as illustrated by the profit line AB. If however, emission standards made 97 percent collection efficiency necessary, no profit would be achieved at the break-even point D. For collection efficiency greater than 97 percent, equipment costs would exceed recovery costs. At 99 percent efficiency, for example, control equipment would cost the amount shown by FH, and the value recovered would be the amount GH. The difference FG would represent an expense and can be considered as the net control cost.

The cement industry is one example where return of the collected material to the process is commonly practiced. A survey conducted in 1956 shows that, out of 383 kilns, a total of 349 return collected dust to the process.[14] Not only does recovered dust, in such situations, have value as a raw material, but its recovery also reduces disposal costs and decreases other related costs for the preparation of raw materials used in the process.[15]

6.8.5 Recovery of Material for Sale

Although material collected by air pollution control equipment may be unsuitable for return to a process within the plant, it may be suitable for another manufacturing activity. Hence, it may be treated and sold to another firm that can use the material. Untreated pulverized fly ash, for example, which cannot be reused in a furnace, can be sold as a raw material to a cement manufacturer. It also can be used as a soil conditioner, or as an asphalt filler, or as landfill material. For such uses, pulverized fly ash requires no treatment and can be sold for as much as $1.00 per ton. Pulverized fly ash which is treated can yield an even more valuable product. A limited number of utilities, for example, sinter pulverized fly ash to produce a lightweight aggregate which can be used to manufacture bricks and lightweight building blocks.

At the present time, however, the sale of raw or treated collected process material usually does not offer an opportunity to offset control costs to a significant extent.

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7. CURRENT RESEARCH IN CONTROL OF PARTICULATE MATTER

A total of 501 identified projects relating to air pollution research were active in 1966.[1] Of these projects, only 16 related directly to research on the control of particulate matter. Five of the 16 projects were financed by the Federal Government (both as in-house and contract projects), and the rest were performed by control equipment manufacturers, public utilities, and some of the larger basic industries.

To provide the research and development necessary to keep pace with the particulate pollution problem and the increasing requirements for improved control, the National Air Pollution Control Administration (NAPCA has undertaken a series of pollution device development system studies. These studies will be conducted by industrial organizations under contract to NAPCA. Their purpose is to systematically identify and carry out research needed to improve the performance and extend the application of major pollution control equipment.

These studies include research on high-temperature bag filtration directed toward increasing bag life and determining the mechanisms that cause bags to rupture.[2] Additional studies are under way to determine performance under various dust inlet feed modes and the effects on filtration of particle size distribution along the filter bag. In another study, the potential of fabric filters for controlling fly ash emissions from power plants burning pulverized coal was investigated.[3]

Combustion research at the NAPCA includes an evaluation of emissions from a pilot trench incinerator.[4] Laboratory investigations into the effects of fuel additives, burner operation, and burner modifications on particulate emissions from oil combustion are being conducted.[5]

Five basic types of wet scrubbers are being studied in an attempt to relate collection efficiency to cost of operation, to improve scrubber effectiveness in the control of incinerator emissions, and to evaluate the scrubber as a gas-liquid contactor. A 100- to 500-cfm test unit was constructed to carry out these investigations.[6]

Contract studies currently being conducted by NAPCA pertain to systems analysis studies covering both theory and application of the various modes of control of particulate matter.

A research program in the field of high-temperature electrostatic precipitation is being conducted by the U.S. Bureau of Mines. Data from a pilot plant at which fly ash is collected show collection efficiencies in the 90 to 98 percent range at a temperature of 1460°F. and a pressure of 80 psig.[7]

Research by universities and manufacturers is under way to determine the effects of sparking rates and gas and dust flow on collection efficiencies of electrostatic precipitators.[8, 9]

Wet scrubber research includes a study of the parameters affecting particle collection in a venturi scrubber [10] and removal of particles by foam in a sieve plate column.[11] Investigations into the performance parameters of the flooded disc scrubber have been reported.[12, 13]

Cloth filtration application studies by private companies are under way on large oil- and coal-fired steam generators [14, 15] and sinter plants.[16]

Additional research is being conducted by equipment manufacturers in an effort to improve technology on the collection of particulate matter.

The October 1968 issue of the Journal of the Air Pollution Control Association is devoted entirely to current aerosol research progress reports.

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☆ U. S. GOVERNMENT PRINTING OFFICE : 1969—347-411/29

National Air Pollution Control Administration Publication No. AP-51